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Design, Fabrication, and Operation of Capsules for the Irradiation Testing of Candidate Advanced Space Reactor Fuel Pins

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DESIGN, FABRICATION, AND OPERATION OF CAPSULES FOR THE IRRADIATION TESTING OF CANDIDATE ADVANCED SPACE REACTOR FUEL PINS

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ABSTRACT

Fuel irradiation experiments were designed, built, and operated to test uranium mononitride (UN) fuel clad in tungsten-lined T-111 (Ta–8% W–2% Hf) and uranium dioxide (UO_2) fuel clad in both tungsten-lined T-111 and tungsten-lined Nb–1% Zr. A total of nine fuel pins was irradiated (four containing porous UN, two containing dense, nonporous UN, and three containing dense UO_2) at average cladding temperatures ranging from 931 to 1015°C. The UN experiments, capsules UN-4 and -5, operated for 10,480 and 10,037 hr, respectively, at an average linear heat generation rate of 10 kW/ft. The UO_2 experiment, capsule UN-6, operated for 8333 hr at an average linear heat generation rate of ~5 kW/ft.

Following irradiation, the nine fuel pins were removed from their capsules, externally examined, and sent to the NASA Plum Brook Facility for more detailed postirradiation examination. During visual examination, it was discovered that the cladding of the fuel pin containing dense UN in each of capsules UN-4 and -5 had failed, exposing the UN fuel to the NaK in which the pins were submerged and permitting the release of fission gas from the failed pins. A rough analysis of the fission gas seen in samples of the gas in the fuel pin region indicated fission gas release-to-birth rates from these fuel pins in the range of 10^{-5}.

1. INTRODUCTION

The National Aeronautics and Space Administration (NASA) investigated a fast-spectrum liquid-metal-cooled reactor concept for space power applications.[1] Part of the fuel development program for this reactor concept was conducted jointly by NASA and Oak Ridge National Laboratory (ORNL) in three irradiation experiments operated in the Oak Ridge Research Reactor (ORR).

The reference reactor fuel pin consisted of uranium mononitride (UN) clad in T-111 (Ta–8% W–2% Hf), which contained a thin tungsten liner between the fuel and cladding to prevent a chemical reaction between the two. Six simulated (smaller than reference) fuel pins containing either dense or porous UN were irradiated in capsules UN-4 and -5. The UO_2 pins, one clad in T-111 and two clad in Nb–1% Zr, were irradiated in capsule UN-6. The UN-6 test was to serve as a basis for comparison between UN and UO_2 irradiation performance.

This report discusses the design, fabrication, operation, and initial disassembly of three irradiation capsules. The two capsules containing UN fuel were irradiated for 10,480 and 10,037 hr at an average linear heat generation rate of ~10 kW/ft. The capsule containing the UO_2 fuel pins operated for 8333 hr at ~5 kW/ft. Following irradiation, the nine fuel pins were recovered, examined, and shipped to theNASA Plum Brook Facility for detailed postirradiation examination.

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1. M. A. Keasner, H. W. Davison, and A. J. Diaguila, *Conceptual Design of a Compact Fast Reactor for Space Power*, NASA TM X-67859 (1971).

2. IRRADIATION FACILITY

The three test capsules were irradiated in the ORR poolside facility, a general arrangement of which is shown in Fig. 1. Capsules UN-4, -5, and -6 were located in poolside positions P3-B, P3-A, and P2-B respectively. The general arrangement of these and other ORR experimental facilities is shown in Fig. 2.

The facility provides a means for moving each capsule horizontally over a distance of 20 in. with respect to the reactor to obtain the desired neutron flux for a particular heat generation rate and/or fuel cladding temperature.

The gas supply system of the facility is capable of supplying any type of gas to the primary and secondary containment systems of the capsules. A schematic flow diagram for capsule UN-4 as it was incorporated in the facility is presented in Fig. 3. The other two capsules had identical gas systems.

3. EXPERIMENTAL ASSEMBLY

Description of the experimental assembly is divided into three parts: the fuel pin designs, the capsule design, and the instrumentation used to monitor the tests.

3.1 Fuel Pin Design

The general arrangement of fuel pins irradiated in this series is shown in Fig. 4. The types of fuel tested were dense and porous UN in capsules UN-4 and -5 and dense UO_2 in capsule UN-6. The purpose of irradiating both UN and UO_2 was to compare the effects of irradiation on the two fuels under similar, though not identical, operation conditions.

Two types of fuel cladding were used: T-111 for all fuel pins of UN-4 and -5 as well as the middle fuel pin of UN-6 and Nb–1% Zr for the top and bottom fuel pins of UN-6. Each fuel pin was 0.375 in. in outer diameter and 4.5 in. long. The cladding ID was 0.318 in., and each fuel pin had a 0.316-in.-OD tungsten liner which was 0.003 in. thick.

The fuel pellet stack height was 3.0 in., and on either end of the fuel was a 0.300-in.-long tungsten spacer with a 0.300-in. OD and a 0.240-in. ID. The remaining length within the cladding was taken up by a series of tungsten washers and T-111 spacers in the form of spherical segments.

The 0.250-in.-long fuel pin end caps were fabricated with male-female extensions so that the three fuel pins in each capsule could be joined with a 0.250-in. gap between each fuel pin. The fuel pin designs are summarized in Table 1, and the preirradiation data for the fuel pins are presented in Appendix A.

3.2 Capsule Design

The general configuration of the three capsule experiments is shown in Fig. 5. Each capsule contained three fuel pins which were designated top, middle, and bottom. The fuel pins were immersed in NaK, and thermocouples were placed in the NaK to obtain, as nearly as possible, the surface temperatures of the fuel cladding.

The NaK and its blanket gas of helium were enclosed in a vessel made of Nb–1% Zr. A series of spacers was used on the OD of the NaK containment vessel to position the NaK vessel and create a uniform gas gap between the vessel and the primary containment. In capsules UN-4 and -5, nine centering spacers (three sets of three spacers each) were used to provide the desired gas gap at operating temperatures. Twelve additional spacers (three sets of four spacers each) were added in capsule UN-6 when it was discovered that the spacers as originally designed were not high enough to keep the NaK

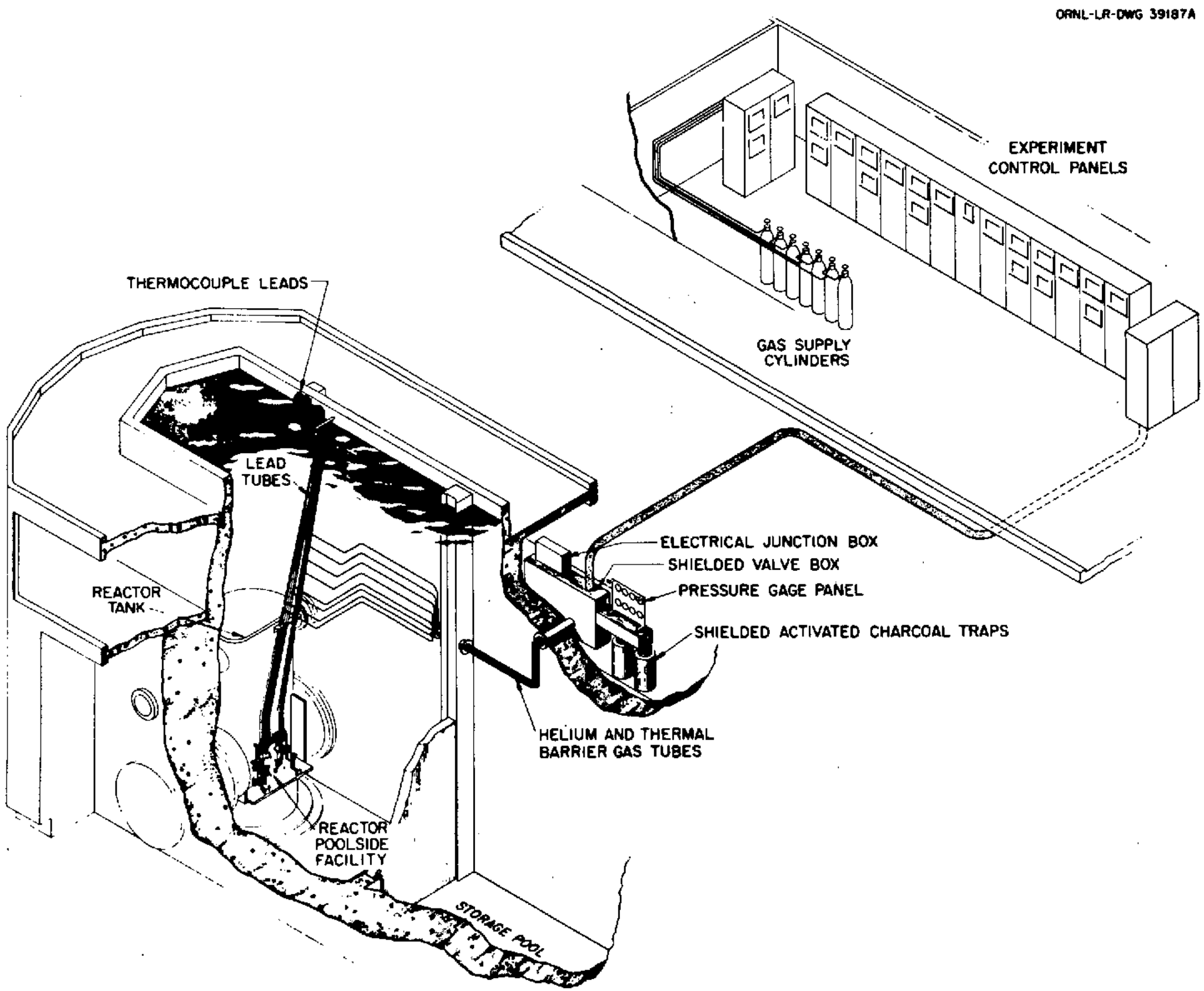

Fig. 1. General arrangement of poolside irradiation facilities in the ORR.

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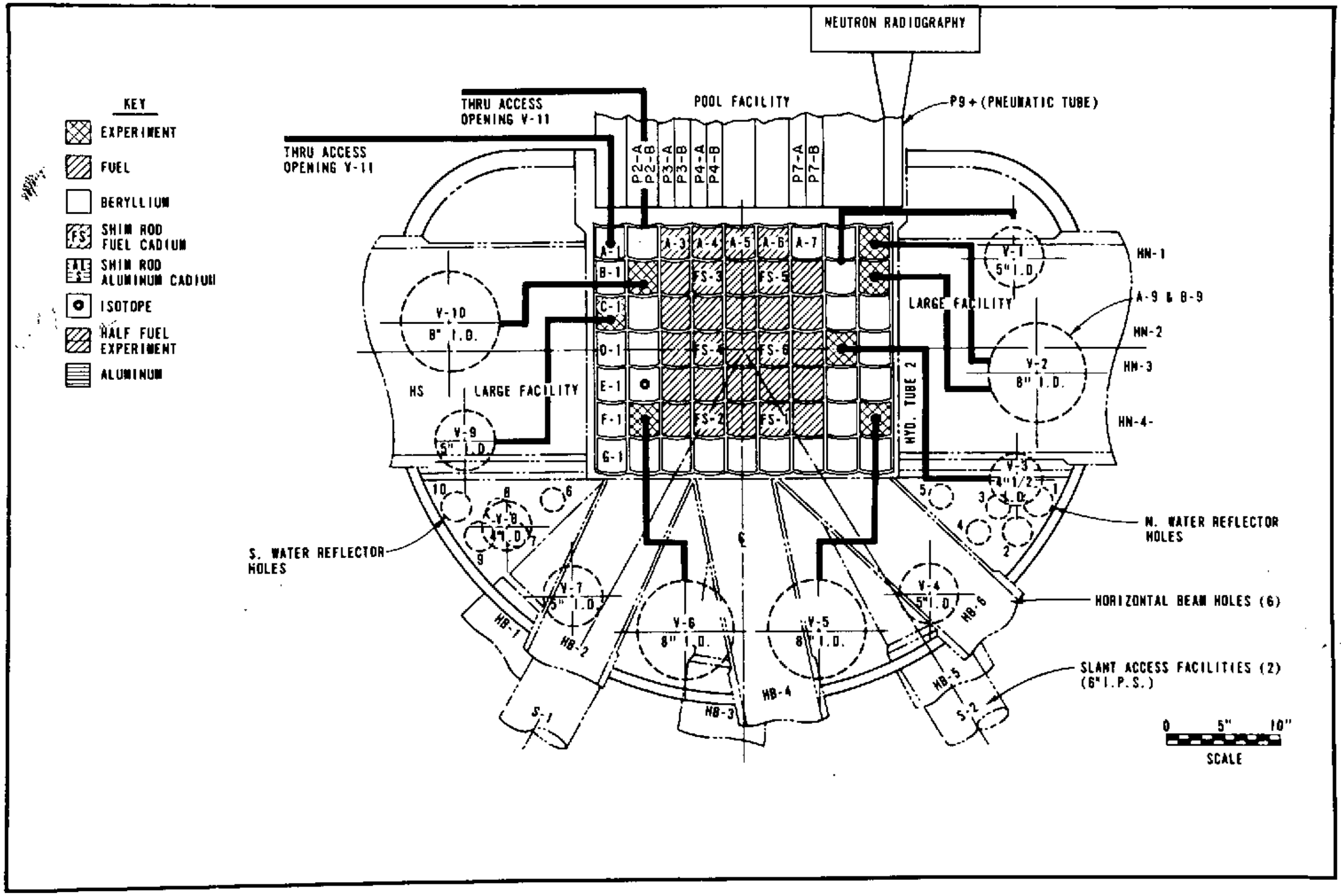

Fig. 2. General arrangement of ORR experimental facilities.

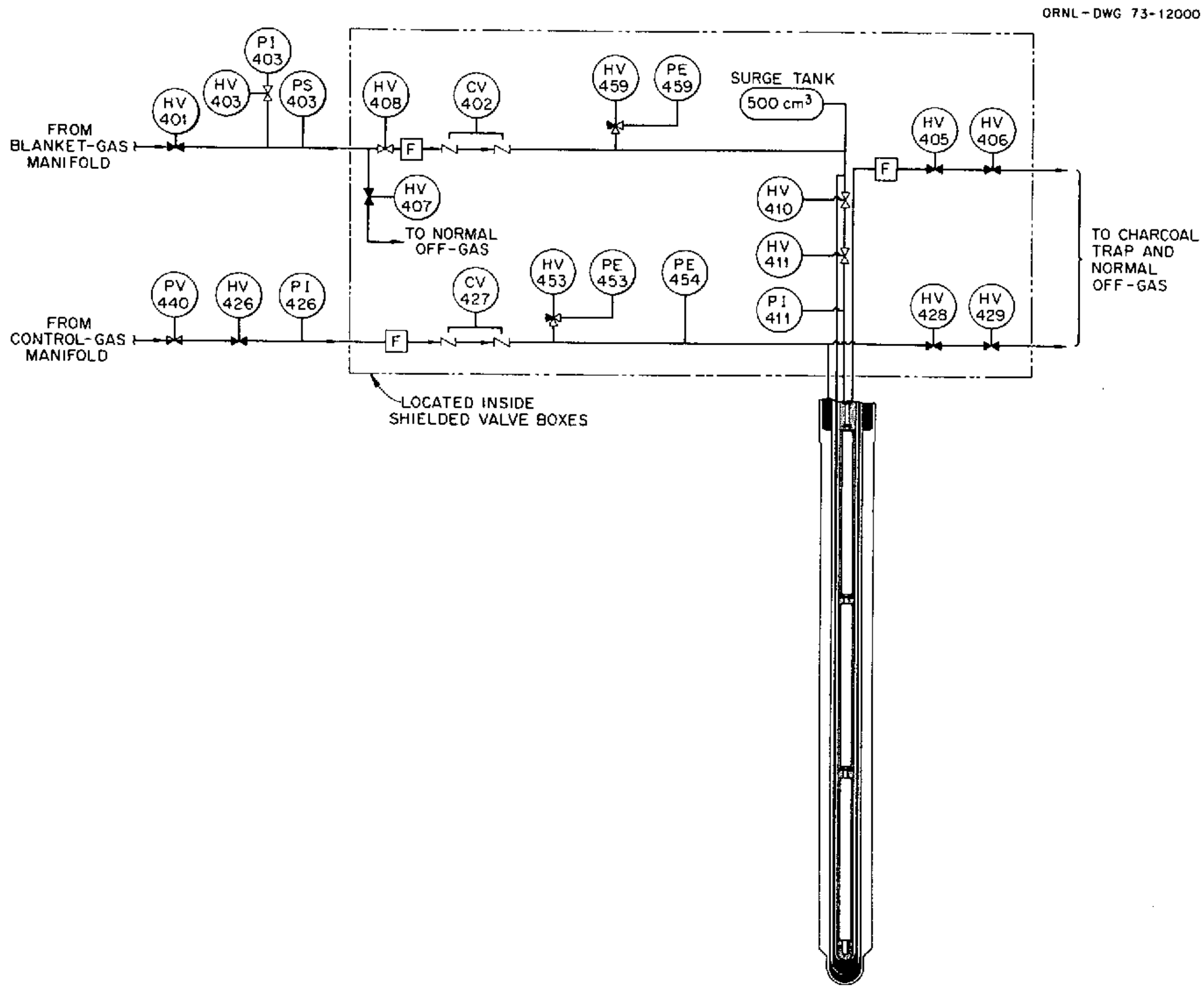

Fig. 3. Schematic flow diagram for capsule UN-4.

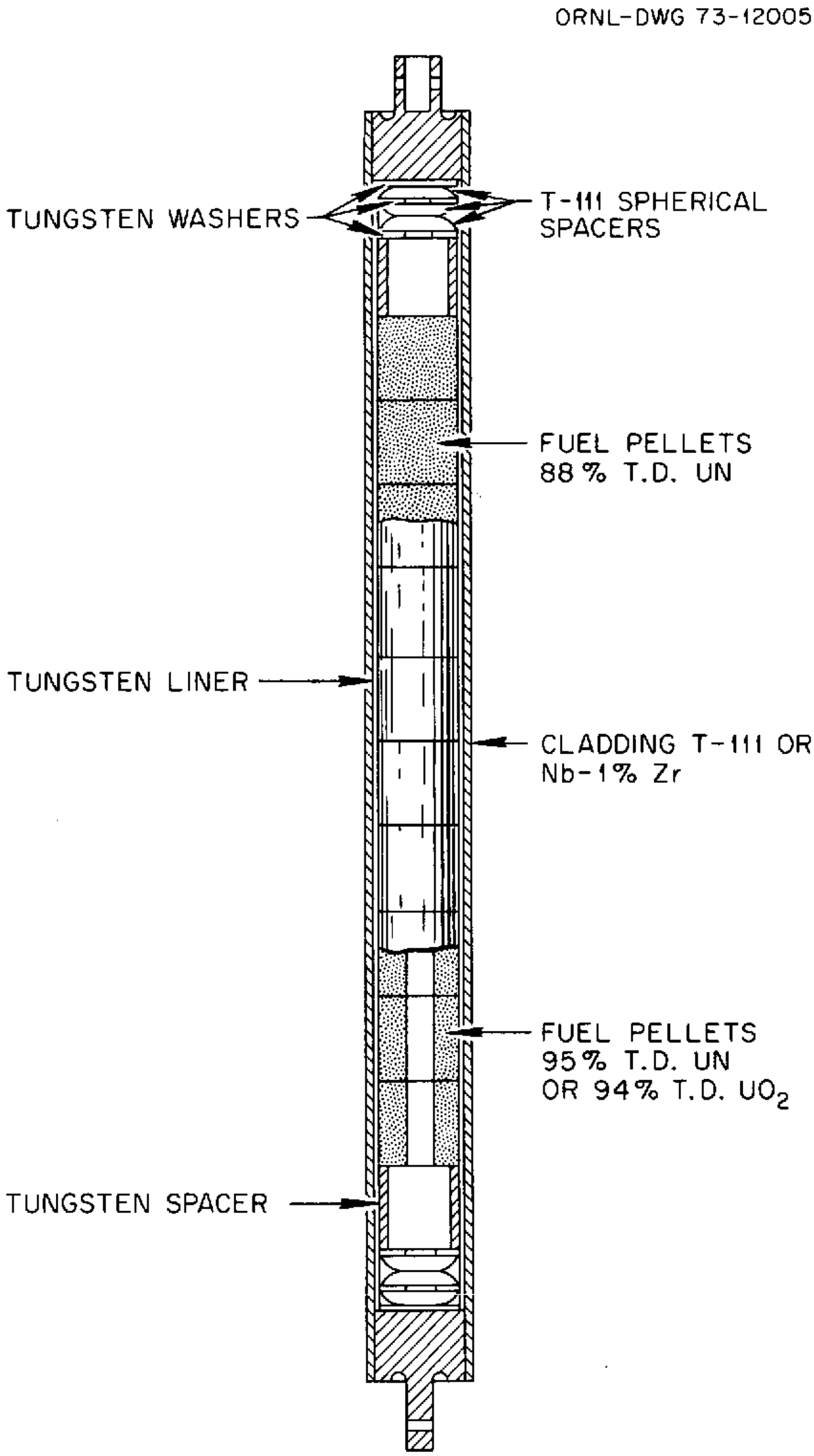

Fig. 4. General arrangement of fuel pins irradiated in capsules UN-4, -5, and -6.

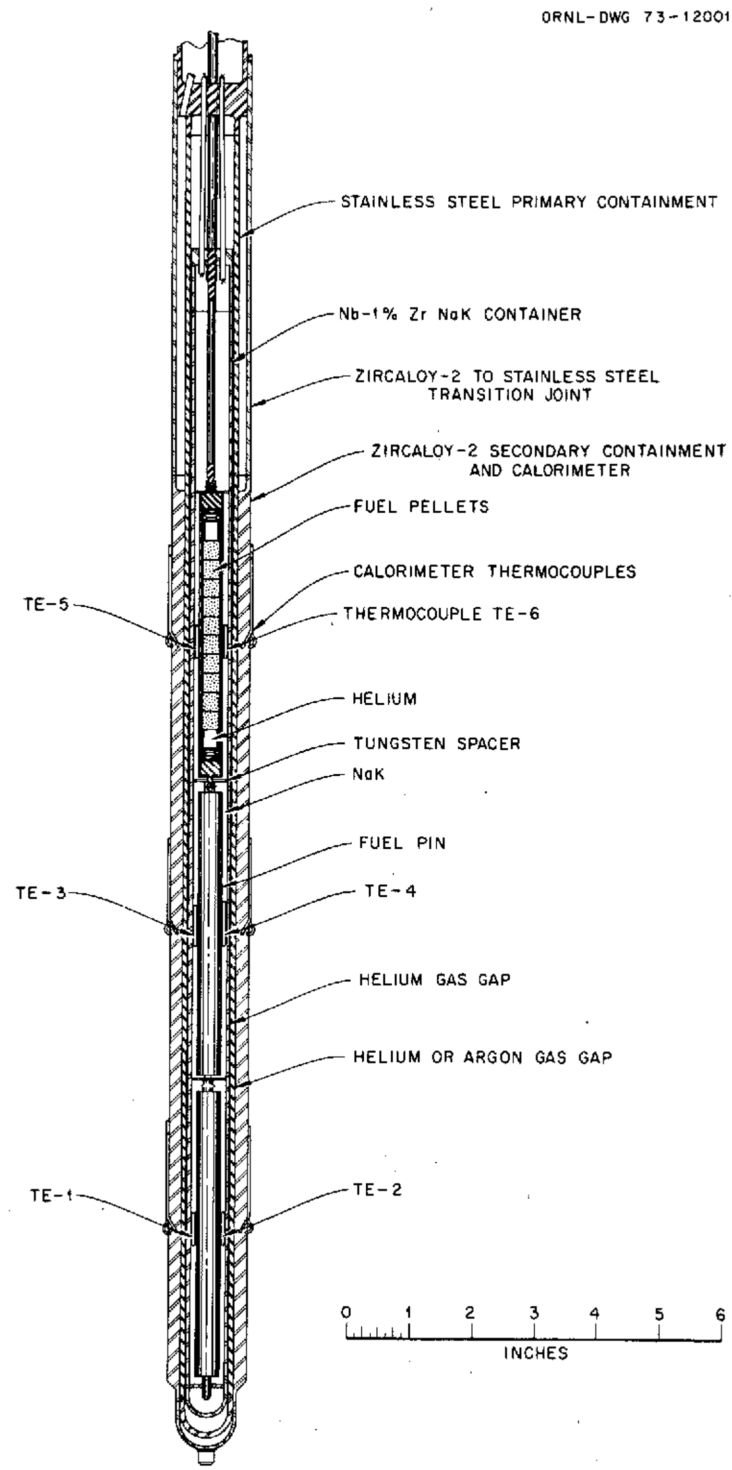

Fig. 5. General configuration of capsules UN-4, -5, and -6.

Table 1. Summary of fuel pin designs

Capsule	Fuel pin No.	Fuel pin location	Fuel					Cladding material[b]
			Material	Type pellet[a]	Density (% theoretical)	Enrichment (^{235}U)		
UN-4	10	Top	UN	Solid	85	20		T-111
	11	Middle	UN	Solid	85	11		T-111
	12	Bottom	UN	Annular[c]	95	11		T-111
UN-5	13	Top	UN	Solid	85	20		T-111
	14	Middle	UN	Annular[c]	95	11		T-111
	15	Bottom	UN	Solid	85	11		T-111
UN-6	16	Top	UO_2	Annular[d]	95	10		Nb–1% Zr
	17	Middle	UO_2	Annular[d]	95	10		T-111
	18	Bottom	UO_2	Annular[d]	95	8		Nb–1% Zr

[a]Pellet outside diameter = 0.308 in.
[b]All fuel cladding was 0.375 in. OD × 0.0285 in. wall thickness.
[c]Inside diameter of UN annular pellets = 0.090 in.
[d]Inside diameter of UO_2 annular pellets = 0.085 in.

vessel centered within the primary containment tube. In subsequent discussions, this gas gap is referred to as the "large gas gap."

The primary container, made of type 304 stainless steel, was surrounded by an outer container which served the dual function of secondary containment and calorimeter. For the latter function, a thick wall was required, and Zircaloy-2 was used because of its relatively low neutron absorption cross section. Operation of the calorimeter was based on a measurement of the temperature drop across a continuous metal wall. This Zircaloy-2 container was joined to the stainless steel bulkhead by a special transition joint which was made by a commercial coextrusion process. Between the primary and secondary containments, there was a gas gap which was 1.5 mils thick at operating conditions. In subsequent discussions, this gas gap is referred to as the "small gas gap."

The helium pressure over the NaK was held at 225 psig to prevent NaK boiling. This blanket gas system was connected to the large gas gap region between the Nb–1% Zr NaK container and the primary container, so that no ΔP existed across the NaK container. The secondary gas pressure between the primary and secondary containments was maintained at 50 psig. Initially all three capsules used helium in this small gas gap, but the gas was changed to argon in UN-6 to raise the cladding temperature of the fuel pins.

3.3 Instrumentation

The surface temperatures of the fuel pins were measured by six thermocouples located as shown in Fig. 5. For capsules UN-4 and -6, all the thermocouples were Chromel-P/Alumel (C/A); however, in capsule UN-5 each fuel pin had one C/A and one W–3% Re/W–25% Re (W/Re) thermocouple. The construction, preparation, and calibration of these thermocouples are summarized in Chapter 5.

The heat generation rate of each fuel pin was determined by measuring the temperature drop through the Zircaloy-2 secondary container. Four pairs of thermocouple junctions were provided on a common plane corresponding to the midlength of each fuel pin. At the appropriate step in assembly of the capsule, this calorimeter was calibrated by placing an electrical heater inside the container and then placing the subassembly including the 24 calorimeter thermocouples into a drum of water heated to the approximate temperature of the ORR pool. The heater had three heated sections to simulate the fueled regions of the capsule. The relationship of linear fission heat generation to the temperature difference between the inner and outer thermocouples was obtained by energizing the heater to produce given heat generation levels and making the proper correction for the effect of gamma heating. The results of the calibrations are presented in Appendix B.

The 24 C/A thermocouples in the calorimeter were 40-mil-OD, stainless steel sheathed, and were approximately 30 ft long. After a thermocouple was placed in the Zircaloy-2 sleeve, the metal surrounding it was peened to hold the thermocouple in position. The remaining length of the sheath was carried in a conduit that extended the full length of the experiment assembly.

The pressures of the primary gas (NaK blanket gas and large gas gap) and the secondary gas (small gas gap) were monitored with strain-gage pressure transducers mounted in the gas lines, and results were continuously recorded.

A DEXTIR data-acquisition system was used to collect all thermocouple data four times per day. The data collected by this system were reduced by computer daily to determine the corrected cladding temperatures as well as the heat generation rates of the individual fuel pins. The time-averaged heat generation rates and average cladding temperatures were determined monthly. Also, a series of plots were produced monthly by the computer to aid in the analysis of the operation of each of the capsules. These plots included all thermocouple data, the standard deviations of all thermocouples, and the distribution of the fission heat flow through the calorimeter shell.

4. DESIGN ANALYSIS

This chapter includes the results of calculations made to determine the fuel enrichments and gas gap sizes needed to obtain an average cladding temperature of 1000°C and a heat generation rate of 8.6 kW/ft. As indicated in Chapter 6, it was not possible to obtain the specified cladding temperature at 8.6 kW/ft, and the linear power was raised to ~10 kW/ft during operation to achieve this temperature level.

4.1 Neutron Flux Analysis

A neutronic analysis was performed to determine the fuel enrichments necessary to minimize the difference in linear heat generation rates over the length of the capsule. The maximum enrichment was set at 20%, since past experience had shown that this was sufficient to obtain the desired heat generation rate in the top fuel pin, which occupied the lowest neutron flux position of the three fuel pins.

Thermal-neutron flux profile measurements were available for the ORR P3-A and -B positions in which UN-5 and -4, respectively, operated. However, experience with previous capsules of similar design in these positions had shown that these measured flux profiles did not agree with the observed power and burnup profiles. Therefore, rather than use the measured flux profiles, a "best estimate" of the flux profile was used. This best estimate, shown in Fig. 6, is based on the experience gained from other experiments conducted in or near positions P3-A and -B. The same profile was used for the P2-B position because of its proximity.

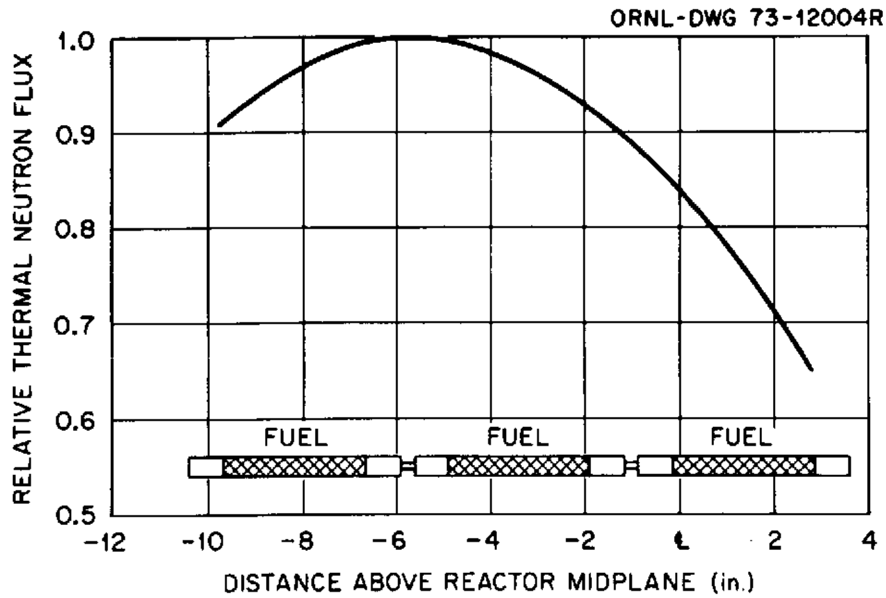

Fig. 6. Expected relative axial flux profile for capsules UN-4, -5, and -6.

The THERMOS code[2] was used to calculate the flux depression as well as the fission cross sections for each type of fuel pin. The results of these calculations were combined with the best estimate of the flux profile to determine the enrichments expected to give the least variation in axial power generation over the life of the test.

For capsules UN-4 and -5, it was found that with 20%-enriched fuel in the top fuel pin and 11% in the middle and bottom fuel pins, the time-averaged power for 10,000 hr should be equal in all three fuel pins.

Capsule UN-6 had more strenuous guidelines, since it had UO_2 fuel and a limitation on the fuel center-line temperature of 1600°C. This limit was selected to minimize fuel redistribution and/or fuel restructuring during irradiation. To meet this center-line temperature requirement with the thermal conductivity of UO_2 and still maintain the cladding at 1000°C, the maximum heat generation rate had to be reduced to an initially predicted value of 6 kW/ft. The neutronic calculations for this capsule were further complicated by the fact that the top and bottom fuel pin cladding was Nb–1% Zr and the middle fuel pin cladding was T-111. The neutron shielding of the T-111 cladding increases with neutron irradiation time as ^{181}Ta is transmuted to ^{182}Ta, which has a thermal-neutron absorption cross section of 17,000 b.

The reduction of the heat generation rate to 6 kW/ft allowed the enrichment of the top fuel pin to be reduced to 10%. Other enrichments were chosen to maintain as closely as possible the same heat generation rates in all three fuel pins throughout the 8000-hr life of the test. This resulted in the use of 10%-enriched fuel for the middle fuel pin and 8%-enriched fuel for the bottom fuel pin.

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2. H. C. Honeck, *THERMOS: A Thermalization Transport Theory Code for Reactor Lattice Calculations*, BNL-5826 (September 1961).

4.2 Thermal Analysis

The linear heat generation rate (or fuel center-line temperature) and temperature of the cladding were specified for these experiments; therefore, thermal design calculations were directed toward sizing the insulating gas gaps. The one-dimensional computer program GENGTC[3] was used for sizing these gaps and obtaining a radial temperature distribution. The predicted radial temperature profile for capsules UN-4 and -5, which were to operate at 8.6 kW/ft, is shown in Fig. 7.

3. H. C. Roland, *GENGTC: A One Dimensional Computer Program for Capsule Temperature Calculation in Cylindrical Geometry*, ORNL-TM-1942 (December 1967).

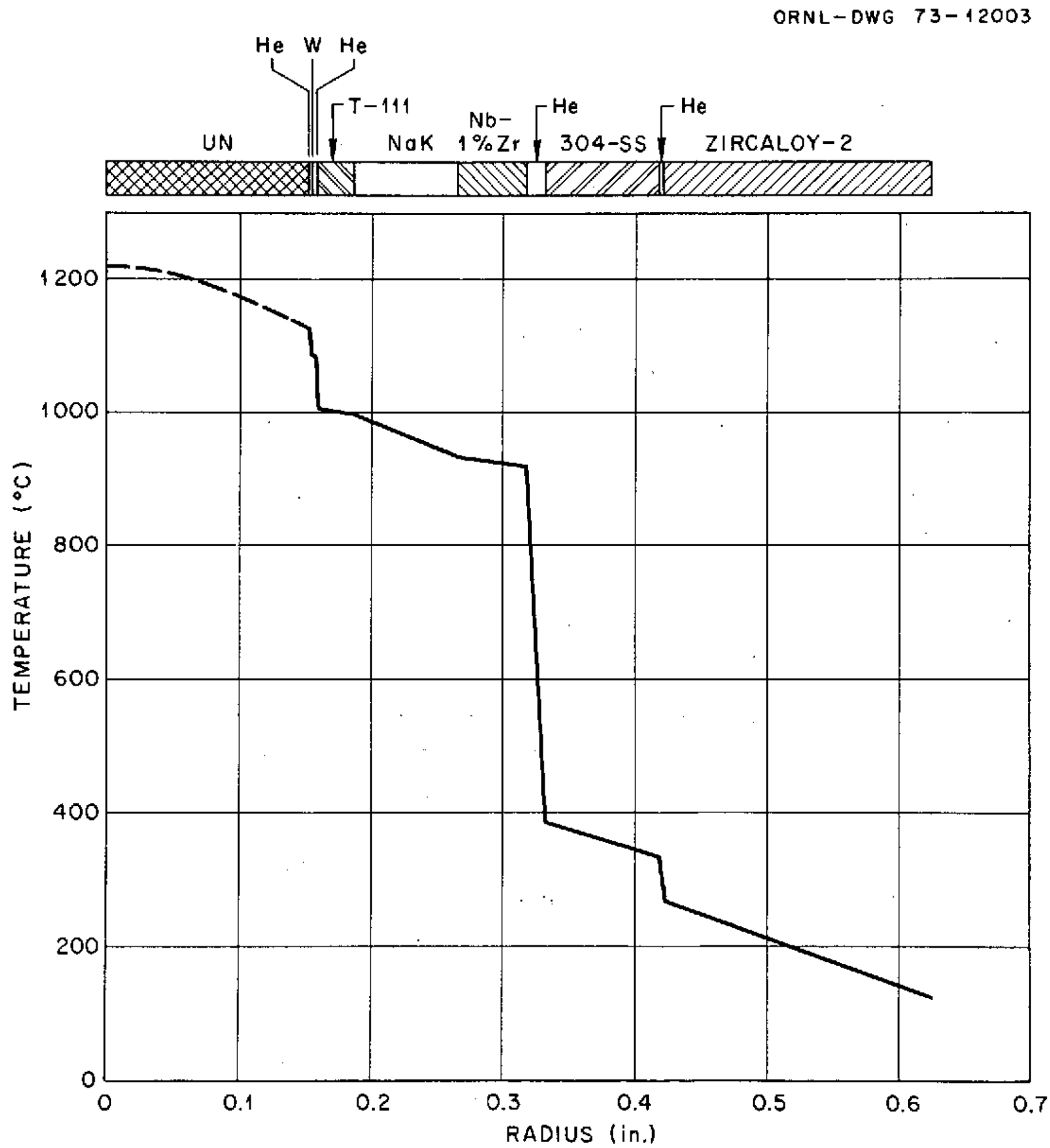

Fig. 7. Predicted radial temperature profile for capsules UN-4 and -5.

The computer code PROFIL[4] was used to determine the temperature profile through the oxide fuel for capsule UN-6. The results of this calculation, along with the GENGTC calculation, produce the predicted radial temperature profile shown in Fig. 8 for operation at 5.1 kW/ft. The figure presents temperatures at 5.1 kW/ft (rather than the previously stated 6 kW/ft), because it was not possible to obtain specified operating conditions at 6.0 kW/ft and the capsule was actually operated at about 5.1 kW/ft.

5. EXPERIMENTAL ASSEMBLY FABRICATION

5.1 Fuel Pin Fabrication

The detailed assembly procedure given in Appendix C was used for assembly of fuel pins for capsule UN-6, since the design of all the fuel pins was very similar.

Basically, assembly of the fuel pins consisted of the following:

1. thorough cleaning and weighing of all components;
2. sorting and fitting of components into assembly packages;
3. welding of bottom end fittings to fuel tubes;
4. inspection of welds, visual inspection, helium leak testing, dye-penetrant inspection, and x-ray radiography;
5. loading of fuel pins;
6. checking of fuel pin exterior for contamination;
7. welding of top (final closure) end fittings to fuel tubes;
8. inspection of welds, visual inspection, helium leak testing, dye-penetrant inspections, and x-ray radiography;
9. x-ray radiography of fuel pin to show positioning of interior components;
10. final machining of end fittings if necessary;
11. photography of fuel pin exteriors;
12. final inspection of fuel pins: diameter, length, and weight measurements;
13. final cleaning, acid pickling, and vacuum heat treating.

The Nb–1% Zr fuel pins for capsule UN-6 were acid pickled and heat treated by slightly different procedures than those used for the T-111 pins. Prior to initial welding, the Nb–1% Zr tubes and end fittings were pickled in a solution of two parts concentrated HF, two parts concentrated HNO_3, and six parts H_2O. The Nb–1% Zr cladding was not heat treated prior to welding and loading. After the final closure weld, the loaded pins were again pickled in the same acid solution and were then wrapped in T-111 foil and heat treated under a vacuum of 10^{-5} torr or better for 1 hr at 2200° F. The completed fuel pins are shown in Figs. 9 to 11 for capsules UN-4, -5, and -6 respectively.

5.2 Cladding Thermocouple Preparation and Calibration

As mentioned previously, the cladding thermocouples used in this series of experiments consisted of 15 Chromel-P/Alumel (C/A) and 3 W–3% Re/W–25% Re (W/Re) thermocouples. Capsules UN-4

4. C. M. Cox and F. J. Homan, *PROFIL: A One-Dimensional Fortran IV Program for Computing Steady-State Temperature Distributions in Cylindrical Ceramic Fuels*, ORNL-TM-2443 and Addendum (March 1969 and August 1969).

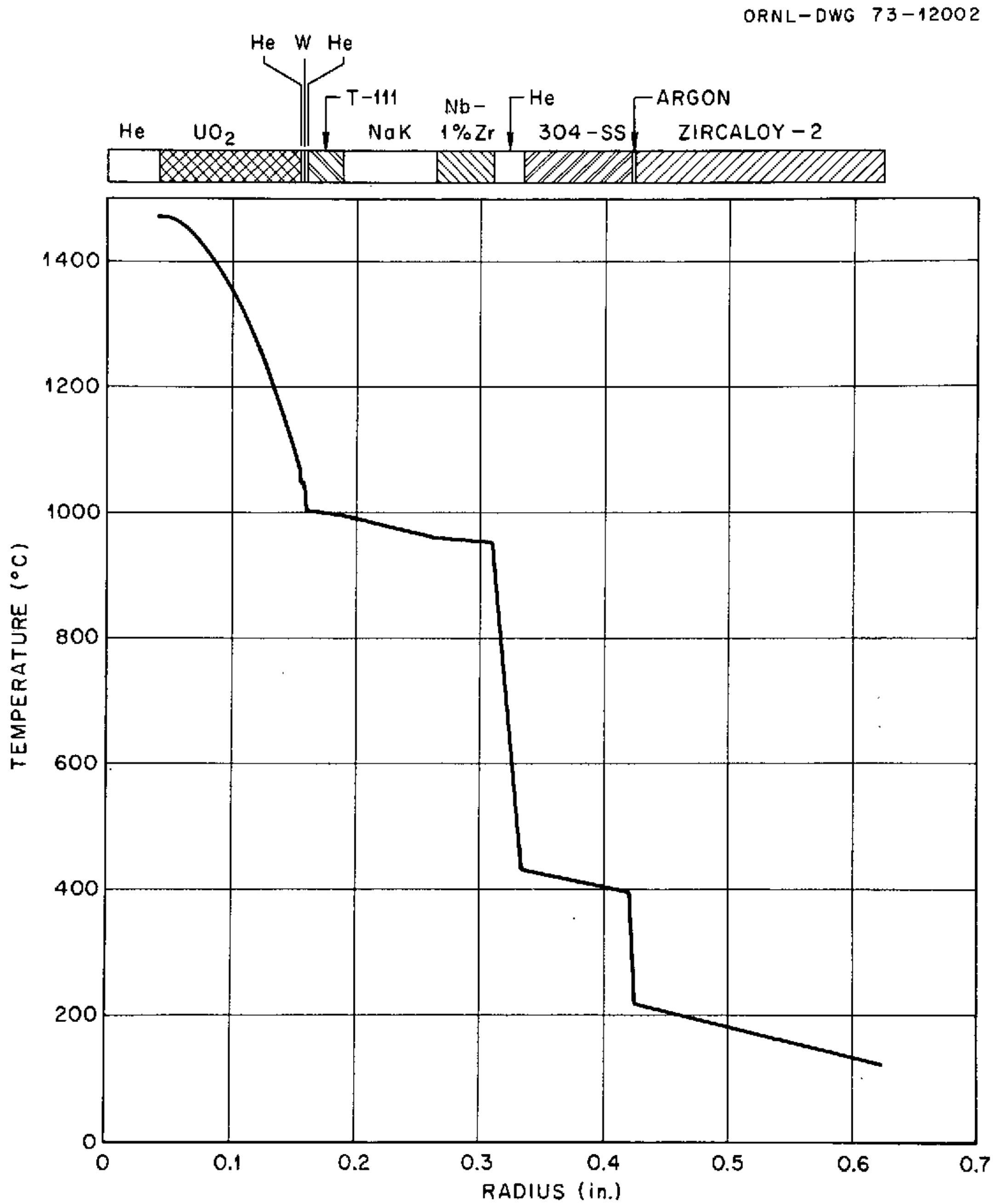

Fig. 8. Predicted radial temperature profile for capsule UN-6.

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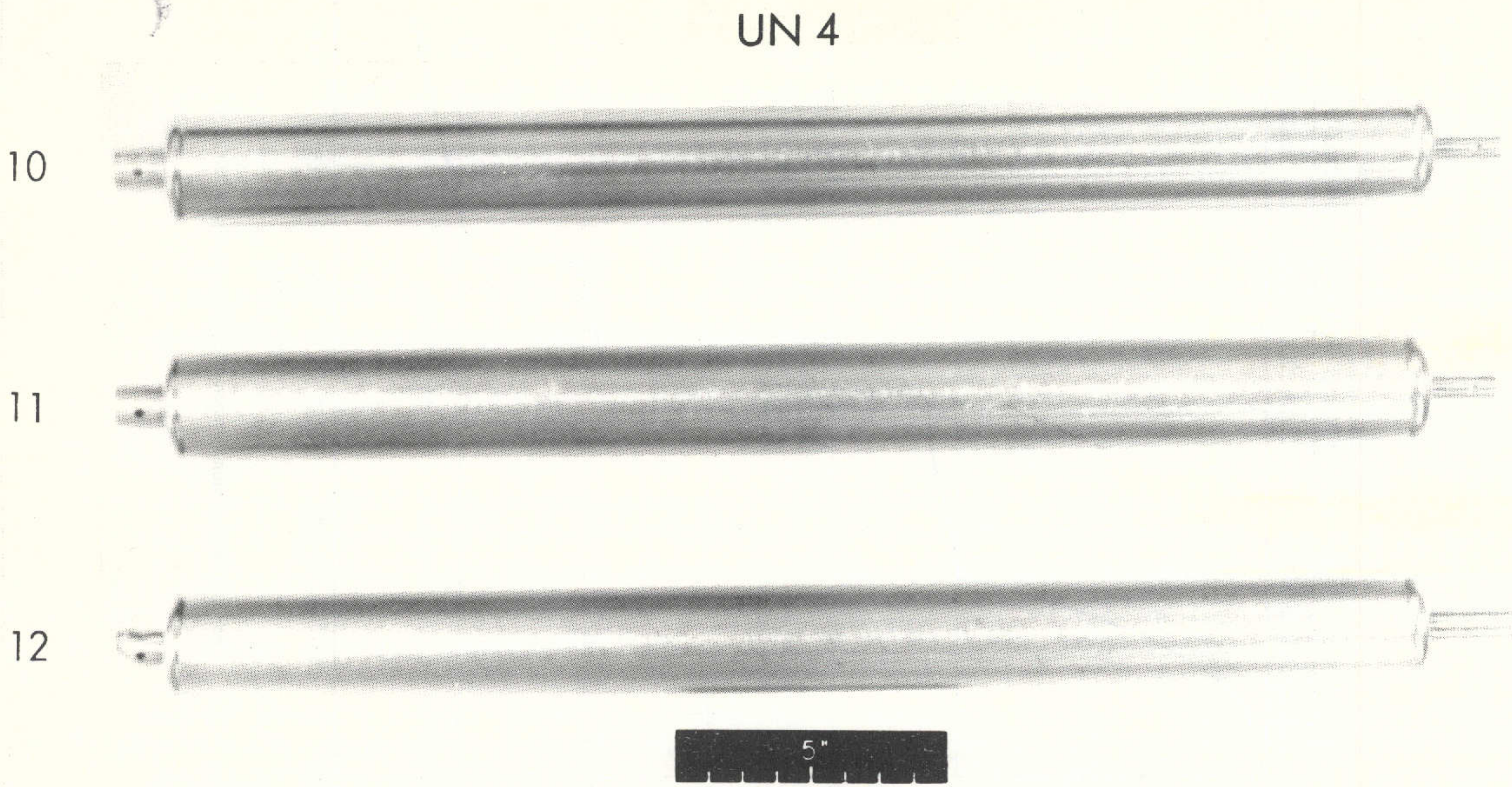

Fig. 9. Completed fuel pins ready for installation in capsule UN-4.

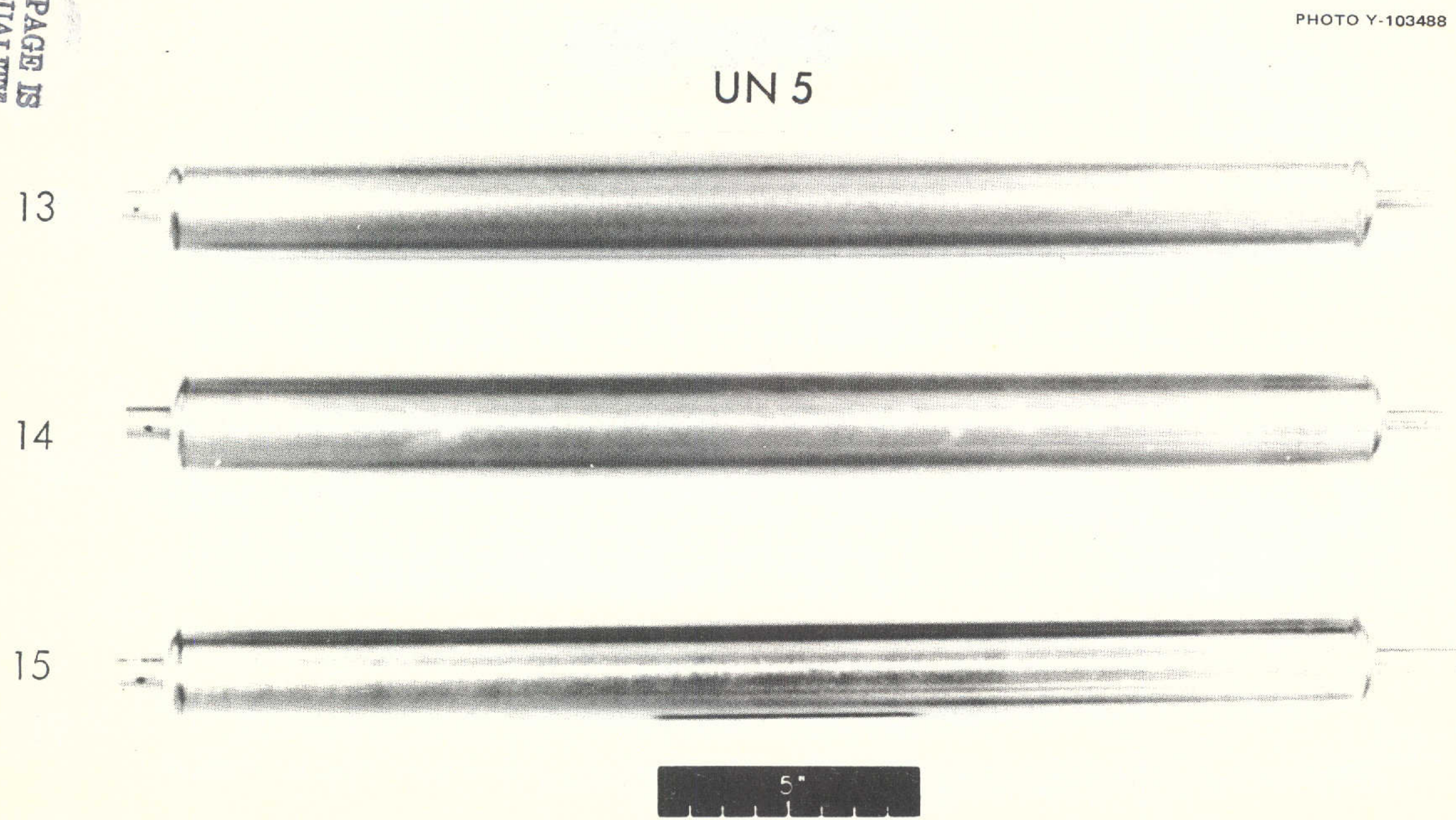

Fig. 10. Completed fuel pins ready for installation in capsule UN-5.

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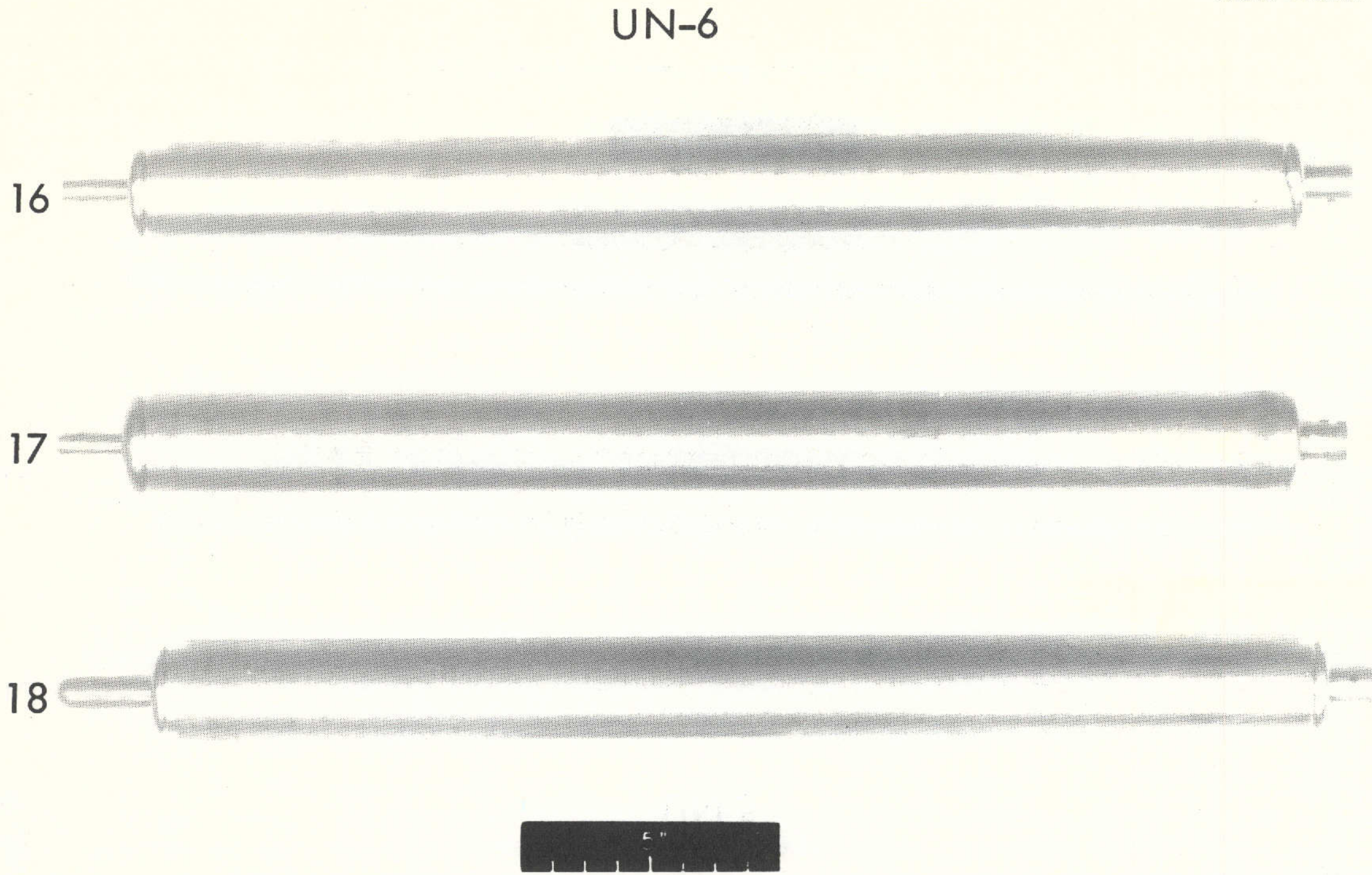

Fig. 11. Completed fuel pins ready for installation in capsule UN-6.

and -6 had two C/A thermocouples strapped to each fuel pin, while capsule UN-5 had one C/A and one W/Re thermocouple strapped to each fuel pin.

Both types of thermocouples were 0.067 in. OD with Nb–1% Zr sheaths. The W/Re had a 0.015-in.-thick sheath, beryllium oxide insulation, and a mechanically swaged plug junction insulated from the sheath. Beyond the junctions, there was approximately $^1/_8$ in. of insulation, a $^1/_{16}$-in. tantalum plug, and an end closure weld made by ORNL. After the end closure weld was completed, the junction ends of the thermocouples were annealed in a vacuum for 2 hr at 1200°C.

The C/A thermocouples had a 0.010-in.-thick Nb–1% Zr sheath with a 0.005-in. tantalum liner, aluminum oxide insulation, and a welded junction that was insulated from the sheath. Beyond the junction there was approximately $^1/_4$ in. of insulation, a $1\,^1/_2$-in. tantalum wire plug, and an end closure weld made by ORNL. After the end closure welds were completed, the entire length of the thermocouples was annealed in a vacuum of $<1.5 \times 10^{-5}$ torr for 2 hr at 1200°C.

After annealing, the low-temperature ends of the thermocouple assemblies were sealed with heat shrinkable tubing in a glove box under an argon atmosphere. Resistance measurements were then made to ascertain the postannealed condition of the thermocouples. Acceptable thermocouples were then installed and brazed to the capsule bulkheads, after which resistance measurements were again made.

A calibration check of each thermocouple was made following brazing into the bulkheads by placing the brazed subassemblies in a vacuum furnace with reference thermocouples placed at the three axial locations of the capsule thermocouple junctions. A photograph of the UN-6 subassembly ready for calibration is shown in Fig. 12. The highest temperatures reached during calibration ranged from 900 to 990°C. The errors for the 18 thermocouples in all three capsules ranged from −0.9 to +1.3% at the highest temperatures. The indicated errors (based on comparison to reference thermocouples) of the two thermocouples at a given junction elevation were similar in value, which suggests that even these small errors were probably due to the junction of the reference thermocouples not being placed at the exact elevation of the capsule thermocouple junctions.

5.3 Capsule Fabrication

A detailed description of the capsule fabrication procedure is presented in Appendix D. In general, the capsule fabrication proceeded as follows.

The fabricated fuel pins were mechanically joined in tandem to each other and to the centering rod which had been brazed in the Nb–1% Zr vessel bulkhead along with the thermocouples. The thermocouples were strapped to the fuel pins with 0.005-in. W/Re wire.

The Nb–1% Zr NaK containment vessel was slipped over the fuel pins and welded to the Nb–1% Zr bulkhead. The primary containment tube was slipped over the Nb–1% Zr vessel and welded to the stainless steel bulkhead. The secondary containment was then positioned over the primary containment and also welded to the stainless steel bulkhead. The remainder of the capsule fabrication consisted of assembling the lead tube which carried the thermocouple leads and gas lines to the point where they could be joined to the existing facilities at the ORR. All welds concerned with the primary or secondary containments or the NaK vessel were x-ray radiographed, dye-penetrant tested, and helium leak checked.

The completed subassembly of capsule UN-6, along with the NaK vessel and primary containment tube, is presented in Fig. 13. As mentioned previously, the NaK vessel for capsule UN-6 was modified by the addition of the 12 centering fins shown in the photograph. A closeup of the middle fuel pin of capsule UN-6 is presented in Fig. 14, which shows the 0.005-in. wire used to strap the thermocouples to the fuel pins. A completed capsule (UN-4) installed in the ORR poolside mockup facility is shown in Fig. 15.

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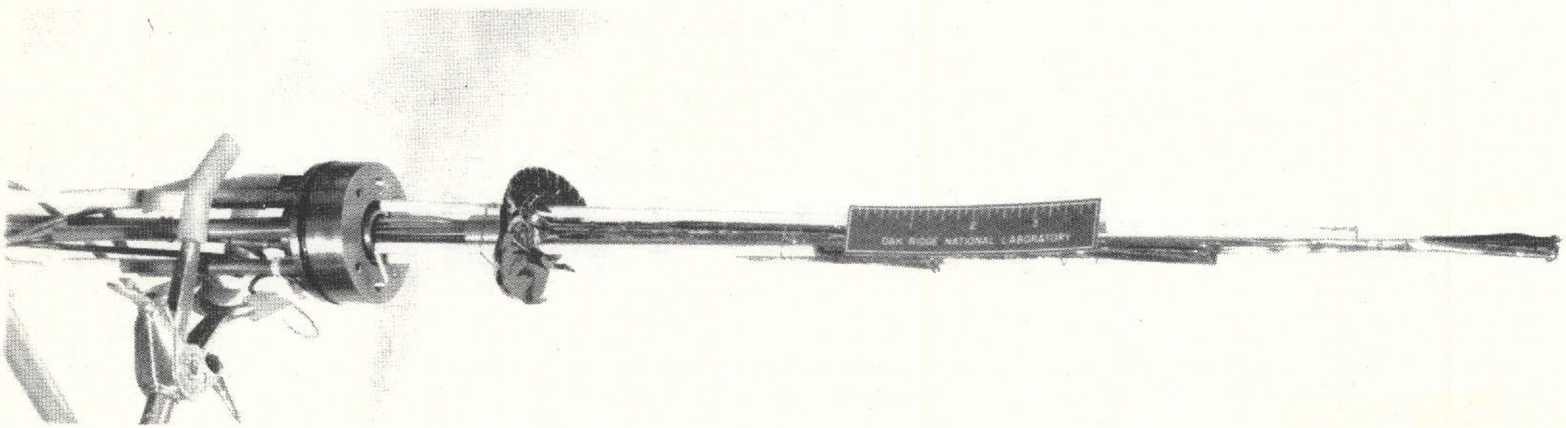

Fig. 12. Thermocouple subassembly of capsule UN-6 ready for thermocouple calibration run.

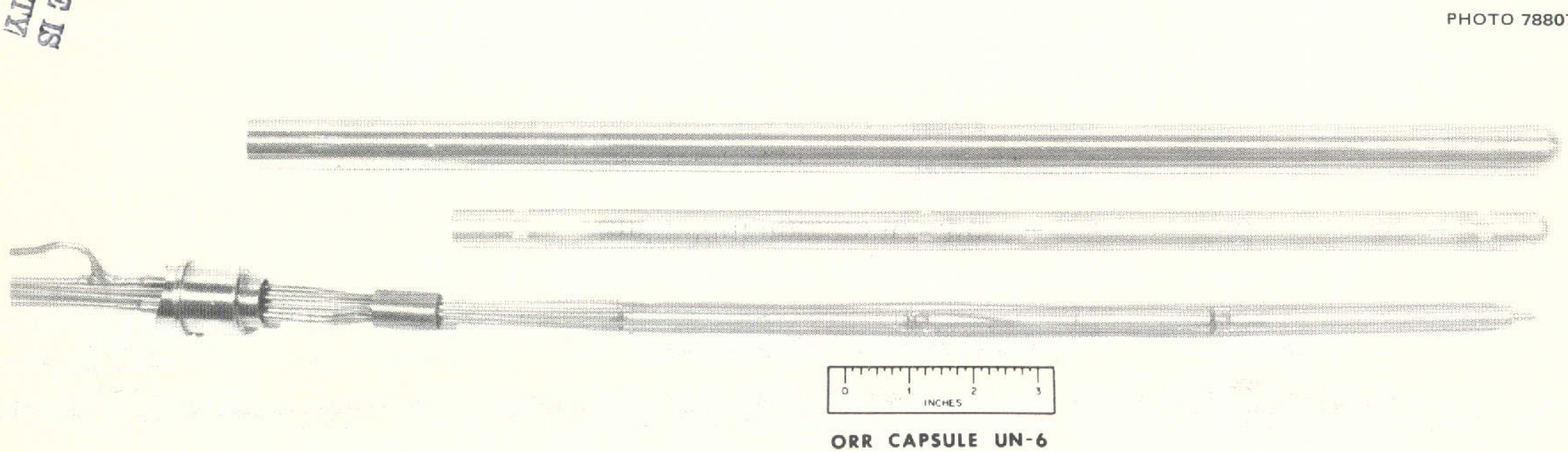

Fig. 13. Internal components of capsule UN-6.

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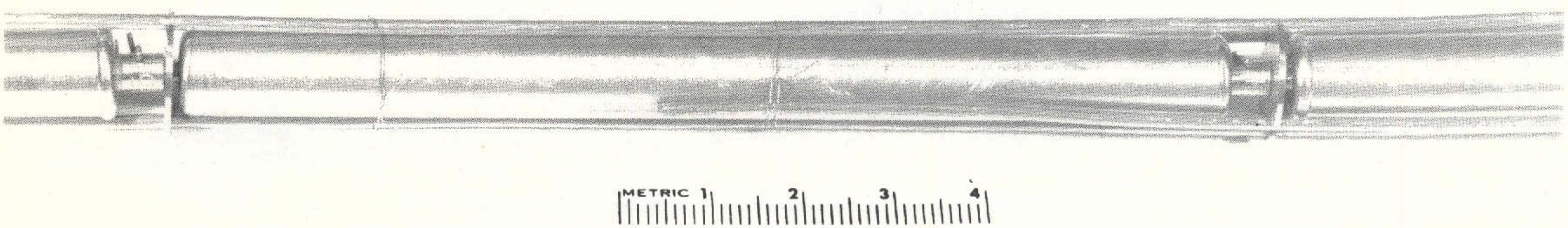

Fig. 14. Closeup of middle fuel pin of capsule UN-6.

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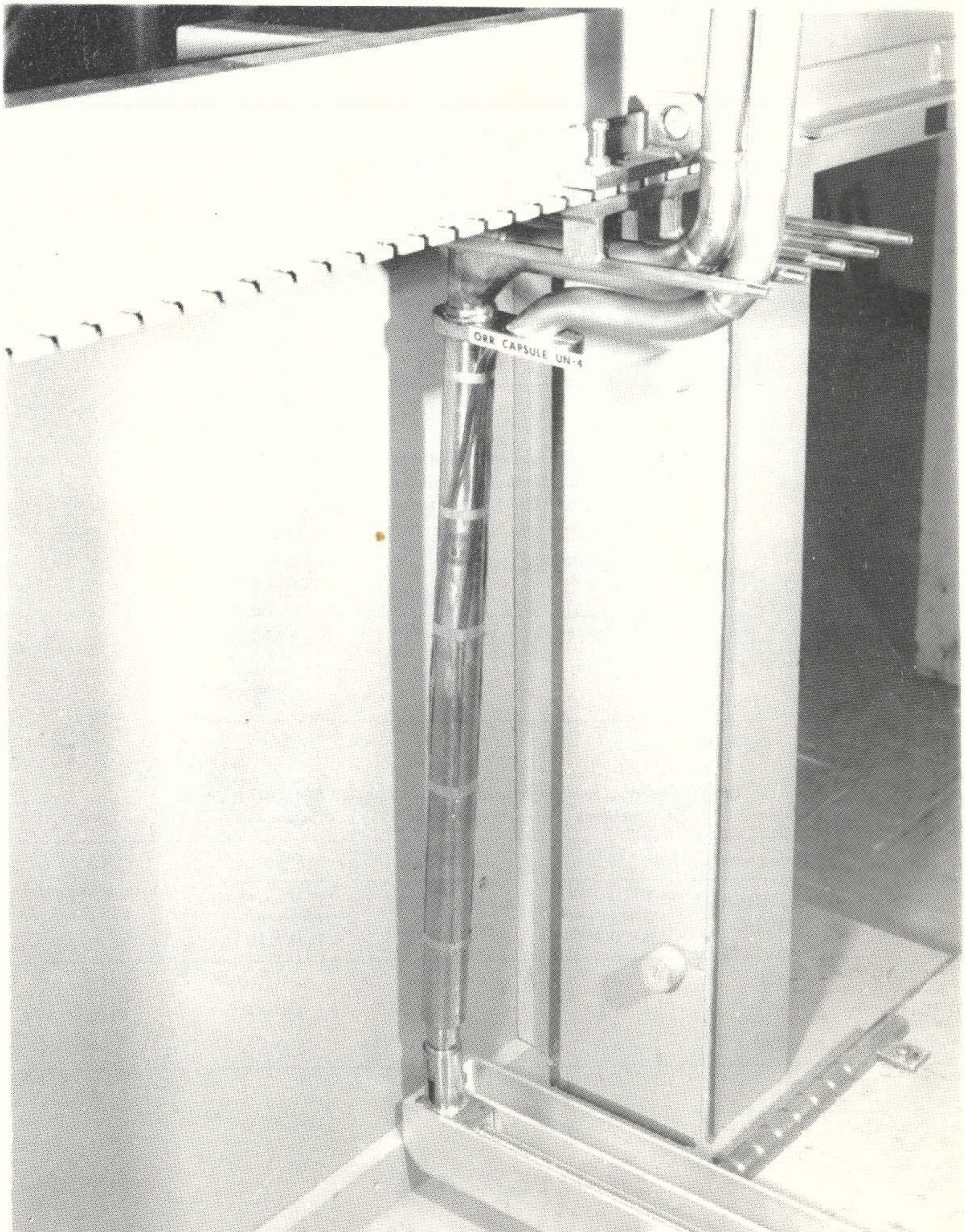

Fig. 15. Completed capsule (UN-4) in ORR poolside mockup facility.

6. OPERATING HISTORY

The average operating conditions and estimated fuel burnups for capsules UN-4, -5, and -6 are summarized in Tables 2 to 4. The detailed operating histories of the capsules are presented below.

Table 2. Average operating conditions and estimated fuel burnup for the three fuel pins of capsule UN-4 after 10,480 hr of irradiation

Fuel pin	Average cladding temp. (°C)	Average heat generation rate (kW/ft)	Estimated burnup (% FIMA)
Top	979	10.2	2.94
Middle	978	10.0	2.88
Bottom	925	9.8	2.82

Table 3. Average operating conditions and estimated fuel burnup for the three fuel pins of capsule UN-5 after 10,037 hr of irradiation

Fuel pin	Average cladding temp. (°C)	Average heat generation rate (kW/ft)	Estimated burnup (% FIMA)
Top	1015	10.2	2.80
Middle	991	9.6	2.63
Bottom	962	9.8	2.68

Table 4. Average operating conditions and estimated fuel burnup for the three fuel pins of capsule UN-6 after 8333 hr of irradiation

	Period covering first 1550 hr		Period from 1550 to 8333 hr		
	Average cladding temp. (°C)	Average heat generation rate (kW/ft)	Average cladding temp. (°C)	Average heat generation rate (kW/ft)	Estimated burnup (% FIMA)
Top	860	4.1	986	4.7	1.54
Middle	845	4.6	931	4.9	1.63
Bottom	895	5.1	953	5.4	1.80

6.1 Capsule UN-4

The irradiation of capsule UN-4 began on Feb. 9, 1971, and ended on July 10, 1972; during this period it operated at cladding temperatures above 800°C for 10,480 hr. The initial operation of the capsule was encouraging; however, several abnormalities developed during later operation which required significant periods of investigation.

Comparisons of calculated and indicated cladding thermocouple temperatures vs linear heat generation rate during initial operation of the capsule are presented in Fig. 16. This figure shows that during this period the indicated thermocouple temperatures of the middle fuel pin were in good agreement with the calculated values. However, the top fuel pin thermocouples appeared to indicate temperatures slightly lower that expected, and the lower fuel pin thermocouples indicated significantly lower temperatures than expected. One explanation for these deviations could be that the NaK container was off center with respect to the primary containment tube center line. On examining the distribution of the heat leaving the capsule through the calorimeter, it became evident that this was in fact the case.

Figure 17 shows the heat generation rate predicted by each pair of calorimeter thermocouples during the initial rise to power. The insertion was controlled to produce a cladding temperature of ~950°C on the bottom fuel element. The figure shows a pronounced variation among the calorimeter readings of the bottom fuel pin, with less variation in those of the upper fuel pin and still less in those of the middle fuel pin. Due to the higher amount of heat being generated by the fuel that is facing the reactor (bottom of Fig. 17), we would expect to see the pattern of calorimeter readings demonstrated by the middle fuel pin if the NaK container were close to perfectly centered.

The variation in heat generation rate shown in the region of the bottom fuel pin suggests that the NaK container in this region was off center in a direction toward the reactor. This condition would cause

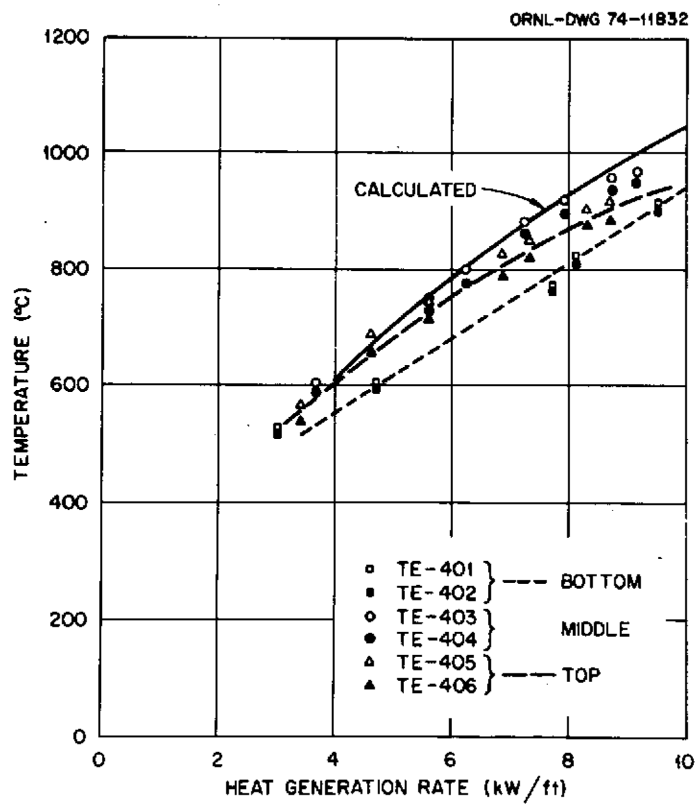

Fig. 16. Comparison of calculated and indicated cladding thermocouple temperature vs heat generation rate for the three fuel pins of capsule UN-4 based on data obtained during initial operation.

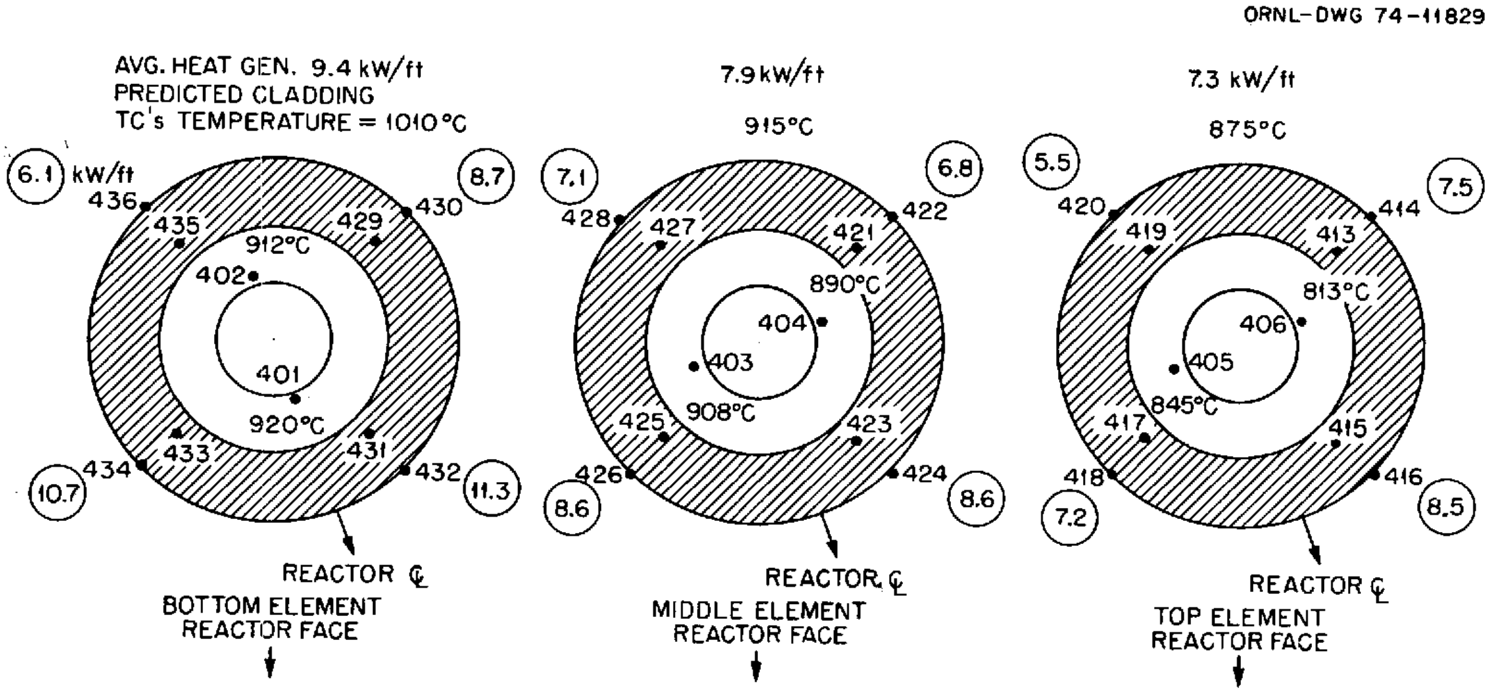

Fig. 17. Distribution of heat flow through the calorimeter of capsule UN-4 during initial rise to power with corresponding temperatures of cladding thermocouples. Circled numbers indicate the heat generation rate predicted by the respective pair of calorimeter thermocouples.

more heat to flow through the calorimeter in the direction of the reactor and would also cause thermocouple 402, which is on the side of the fuel pin away from the reactor (back side), to read slightly higher than expected and cause thermocouple 401, on the side nearest the reactor (front side), to read slightly lower than expected. These two thermocouples were located in the capsule so as to indicate the maximum temperature difference across a fuel pin. (The plane formed by these two thermocouples runs through the center of the reactor.) However, as can be seen in Fig. 17, they indicated almost the same temperature for a given heat generation rate. This off-centered condition would also lower the overall effective thermal resistance between the fuel pin and the pool water, thus explaining why the cladding thermocouple temperatures were lower than expected. The preirradiation neutron radiographs, though not as sharp as desirable, appear to confirm that in the region of the bottom fuel pin the NaK container was slightly closer to the primary containment vessel in a direction toward the reactor.

The NaK container also appeared to be off center in the region of the upper fuel pin, but not as severely as in the region of the lower fuel pin and also not in the same direction. This contention is based on the calorimeter data shown in Fig. 17 and also on the fact that the cladding thermocouples indicated slightly lower than predicted temperatures. The calorimeter data indicated that the upper fuel pin was off center in the approximate direction of thermocouple TE-406. This interpretation was also supported by the fact that TE-406 indicated a somewhat lower temperature than did TE-405 when they should indicate roughly similar temperatures based on their physical locations.

The middle fuel pin was probably the closest to being centered, based on calorimeter data and the fact that the cladding thermocoople temperatures were fairly close to expected values.

The ORR fuel cycle generates a flux peak which moves upward in the irradiation facility during the course of the cycle. During the operation of the capsule, numerous temperature oscillations were indicated by the cladding thermocouples (401 and 402) of the bottom fuel pin. These oscillations occurred only during the early period of a reactor fuel cycle, when the bottom fuel pin was significantly hotter than the middle and top fuel pins. The same type of oscillations appeared during the operation of capsule UN-5; through the use of a multichannel recorder we were able to determine that the oscillations were due to movement of the NaK container within the primary containment. This analysis is described in Section 6.2.

In addition to the temperature oscillations, changes were observed in the temperature levels indicated by the cladding thermocouples for operation at a given heat generation rate. This trend is shown in Fig. 18, which presents a history of the indicated temperatures of all the cladding thermocouples for a linear heat generation rate of 10.2 kW/ft. Because of these temperature level changes, the mode of operational control was changed several times during the irradiation history of the capsule. The operating control modes utilized during the life of the capsule are summarized in Table 5. All the listed modes of operation were established in an attempt to employ the most accurate means of maintaining the cladding surface temperature of the middle fuel pin at 1000° C during the particular time each was in effect.

The significant changes in the indicated temperatures of the cladding thermocouples for a given heat generation rate leads one to question the accuracy of these thermocouples. In fact, it appears that only one thermocouple (TE-406) indicated a reasonable temperature level through the entire life of the test. After 6000 hr of operation, four of the six cladding thermocouples had become grounded and formed parasitic junctions. We were able to determine that the parasitic junctions were located in the region of the top three fuel pellets of the top fuel pin. This determination was reached by measuring the change in wire-to-wire resistance and also by interpretation of response of the thermocouples to known temperature change patterns. During a reactor fuel cycle, temperatures indicated by the faulty

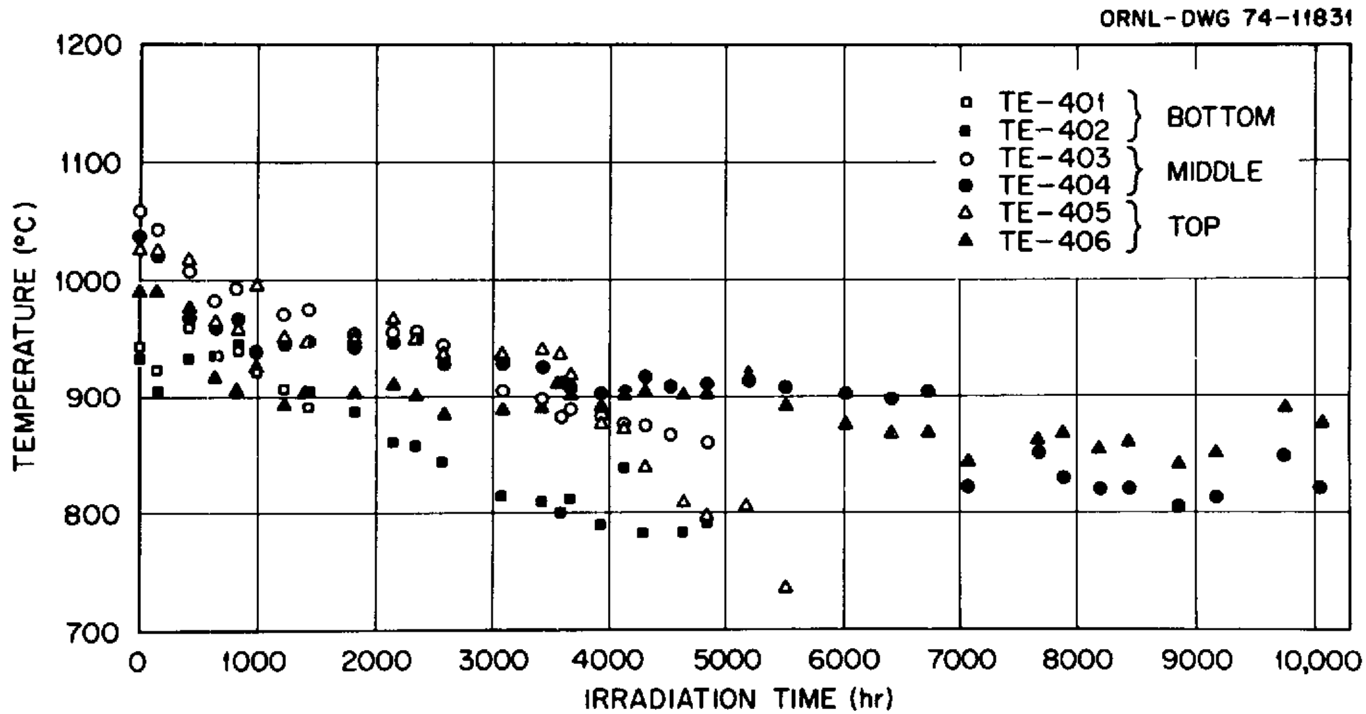

Fig. 18. History of indicated temperatures of the cladding thermocouple of capsule UN-4 while operating at 10.2 kW/ft.
Note: While all thermocouples indicated some sort of temperature at the end of the test, several became unreasonable during the test and were no longer plotted.

Table 5. Method of operation of capsule UN-4 during its 10,480 hr of operation

Accumulated irradiation time (hr)	Method of operation
0–2600	Average indicated temperature of TE-403 and -404 maintained at 960°C
2600–6100	Heat generation rate of middle fuel pin maintained at 10.2 kW/ft
6100–7050	TE-404 maintained at 950°C while observing that middle fuel pin heat generation rate does not exceed 10.8 kW/ft
7050–10,480	Maintained heat generation rate of middle fuel pin at 10.7 kW/ft

thermocouples would rise at a rate comparable to the increase in power experienced by the top fuel pin even though the original junctions were positioned adjacent to fuel pins that were decreasing in power.

After ~7100 hr at power, thermocouple TE-404 also became partially grounded while the capsule was being handled to take neutron radiographs. Although there was no appreciable change in the wire-to-wire resistance, the indicated temperature at a heat generation rate of 10.2 kW/ft dropped 80°C at the next return to power. This drop is quite noticeable in Fig. 18.

Thermocouple performance for all three capsules is reported in Ref. 5.

A routine procedure in operating capsules of this type is to sample the NaK blanket gas for fission products during each major shutdown. Although we now know that the bottom fuel pin in capsule UN-4 failed during irradiation, we did not observe a sufficient amount of fission products in these routine samples to indicate that a fuel pin had failed. After 5500 hr of operation, we did find a trace of ^{133}Xe in a blanket gas sample but dismissed it as being caused by back contamination of the sampling system from another experiment. However, fission products continued to appear in subsequent blanket gas samples, and by the time the irradiation of the capsule was terminated, enough activity was observed to attempt to calculate a release-to-birth (R/B) rate value. Since these capsules were not designed to determine the R/B of UN, any attempt to do so is crude at best; however, we estimated an R/B value on the order of 10^{-5}. As a comparison, NASA found a release of the order of 10^{-4} on similar fuel pins run for 8070 hr (~1% burnup).[6]

Three sets of neutron radiographs were taken of capsule UN-4: one preirradiation set, one after 7060 hr of irradiation, and one at the end of the test. The set taken after 7060 hr showed what appeared to be holes in the cladding of the middle and bottom fuel pins. These holes were not found in postirradiation examination and were dismissed as imperfections in the radiographs. The set of neutron radiographs made at the end of the test showed a major cladding crack in the bottom fuel pin (pin 12). All the neutron radiographs were sent to NASA for further evaluation.

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5. K. R. Thoms, V. A. DeCarlo, and S. C. Weaver, "Experience with High-Temperature Thermocouples Used in Fuel Irradiation Tests," *Trans. Amer. Nucl. Soc.* 15(1), 179–80 (June 1972).

6. Jack G. Slaby et al., *Irradiation of Three T-111 Clad Uranium Nitride Fuel Pins for 8070 Hours at 990° C (1815° F)*, NASA TM X-2878 (1973).

6.2 Capsule UN-5

The irradiation of capsule UN-5 began on Mar. 8, 1971, and terminated on July 10, 1972; during this period it operated at cladding temperatures above 800°C for 10,037 hr.

During the early operation of UN-5, it became apparent that some of the problems encountered with UN-4 were going to be experienced with UN-5. The initial rise to power showed that, as in UN-4, operating temperatures for given heat generation rates would be lower than had been calculated. Calculated and indicated cladding thermocouple temperatures vs linear heat generation rate are compared in Fig. 19, which shows that the deviation from calculated values was about the same for all three fuel pins. Examination of the heat distribution indicated by individual pairs of calorimeter thermocouples again indicated that the NaK container was not concentric within the capsule primary containment tube.

As was the case with capsule UN-4, the control of UN-5 was to maintain the average cladding temperature of the middle fuel pin at a nominal value of 1000°C. However, during the early life of this capsule, the bottom fuel pin operated at a significantly higher heat generation rate at the beginning of a reactor fuel cycle than did the other two fuel pins. Early in a reactor fuel cycle, control consisted of limiting the average cladding temperature of the bottom fuel pin to a maximum of 1100°C. As the reactor fuel cycle progressed and the flux peak moved upward, control would shift to that of maintaining the middle fuel pin at 1000°C. Later in the fuel cycle the heat generation rate of the top fuel pin increased, making it necessary to control by limiting the average cladding temperature of the top fuel pin to 1100°C.

The thermal oscillations noticed in capsule UN-4 were also noticed on the bottom element of UN-5 but were more severe in UN-5, where thermocouple TE-501 would drop as much as 80°C in ~3 sec. In an

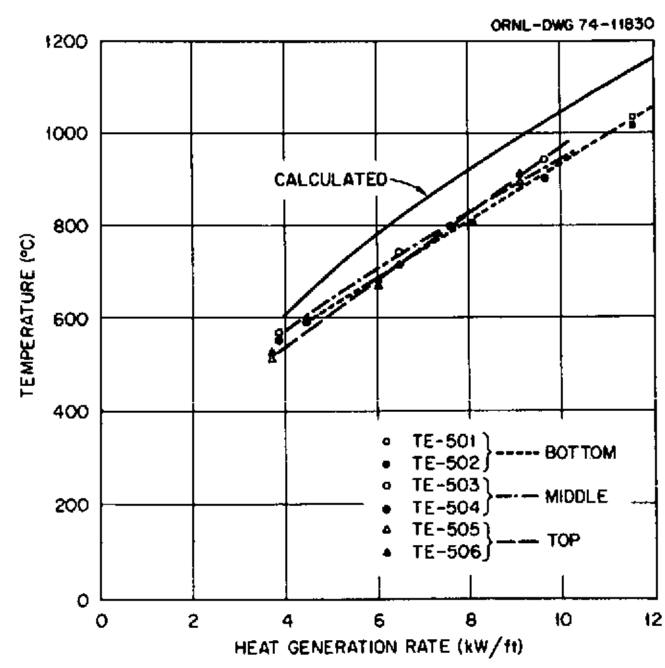

Fig. 19. Comparison of calculated and indicated cladding thermocouple temperature vs heat generation rate for the three fuel pins of capsule UN-5 based on data obtained during early operation.

effort to gain more knowledge as to what was going on inside the capsule, thermocouples which showed oscillations were attached to an eight-channel Sanborn recorder. Figure 20 shows the recorder tracings produced during a typical oscillating period by cladding thermocouples 501, 502, and 503 and by inner calorimeter thermocouples 529, 531, 533, and 535, along with the locations of these thermocouples. As can be seen in the figure, during the oscillating period, the bottom fuel pin cladding thermocouples (501 and 502) both decreased in temperature at the same time. Two of the calorimeter thermocouples (529 and 531) increased in temperature, and two of the calorimeter thermocouples (533 and 535) decreased. These facts indicated that the NaK container was moving in a direction toward thermocouples 529 and 531, thus allowing more heat to flow through the gas gap to the calorimeter on that side and less on the other. The movement caused the NaK container to become more off center, reducing the overall thermal resistance of the gas gap between the NaK container and the stainless steel wall, and caused thermocouples 501 and 502 to decrease in temperature. Thermocouple 503, which was on the middle fuel pin and on the side opposite from the direction of movement, increased in temperature because of the local increase in thermal resistance of the gas gap. These thermal oscillations occurred with greatest severity and highest frequency at the beginning of a reactor fuel cycle, when the bottom fuel pin was significantly hotter than the other two fuel pins.

The thermocouple problems experienced in capsule UN-4 were also present in UN-5 but were not as severe. All the thermocouples of capsule UN-4 appeared to be inaccurate at the end of the test, but one W/Re (TE-503) and one C/A (TE-506) thermocouple continued to indicate reasonable temperature data through the entire 10,037 hr of operation of the UN-5 capsule.

Samples taken of the NaK blanket gas of UN-5 showed no sign of fission gas until the capsule had operated for 7900 hr. After 7900 hr, the amount of activity found was very small and was not at the time attributed to a failed fuel pin. The amount of activity continued to increase in subsequent samples, and at the time the test was concluded, the fission gas being released was roughly equal to that of capsule UN-4 (i.e., equivalent to a R/B ratio on the order of 10^{-5}).

Three sets of neutron radiographs were also made of capsule UN-5: one preirradiation set, one after 9000 hr, and one at the completion of the test. The neutron radiographs made after 9000 hr showed what appeared to be a longitudinal crack in the fuel pellets of the middle fuel pin. The crack appeared to be about 2 in. long and appeared to run through all but the end fuel pellets. Based on the postirradiation appearance of the fuel pin, what we saw was actually a crack in the fuel pin cladding as well as a crack in the fuel itself.

6.3 Capsule UN-6

The irradiation of capsule UN-6 began on Aug. 5, 1971, and terminated on Sept. 10, 1972; during this period it operated at cladding temperatures above 800°C for 8333 hr.

The initial 1550 hr of the test was conducted with the average cladding temperatures 100 to 150°C below the desired 1000°C. Design calculations predicted that a heat generation rate of 6 kW/ft would maintain the cladding at 1000°C and the fuel center line at 1550°C. However, the initial insertion of the capsule showed that we were again not obtaining good agreement between calculated and observed cladding thermocouple temperatures for given heat generation rates. The cladding thermocouple response was about 100°C below calculated values for a heat generation rate of about 6 kW/ft as determined from the calorimeter data.

Because of the 1600°C fuel center-line temperature restriction, we did not feel that we could operate at heat generation rates much higher than 6 kW/ft, because the ΔT from fuel cladding to fuel center line

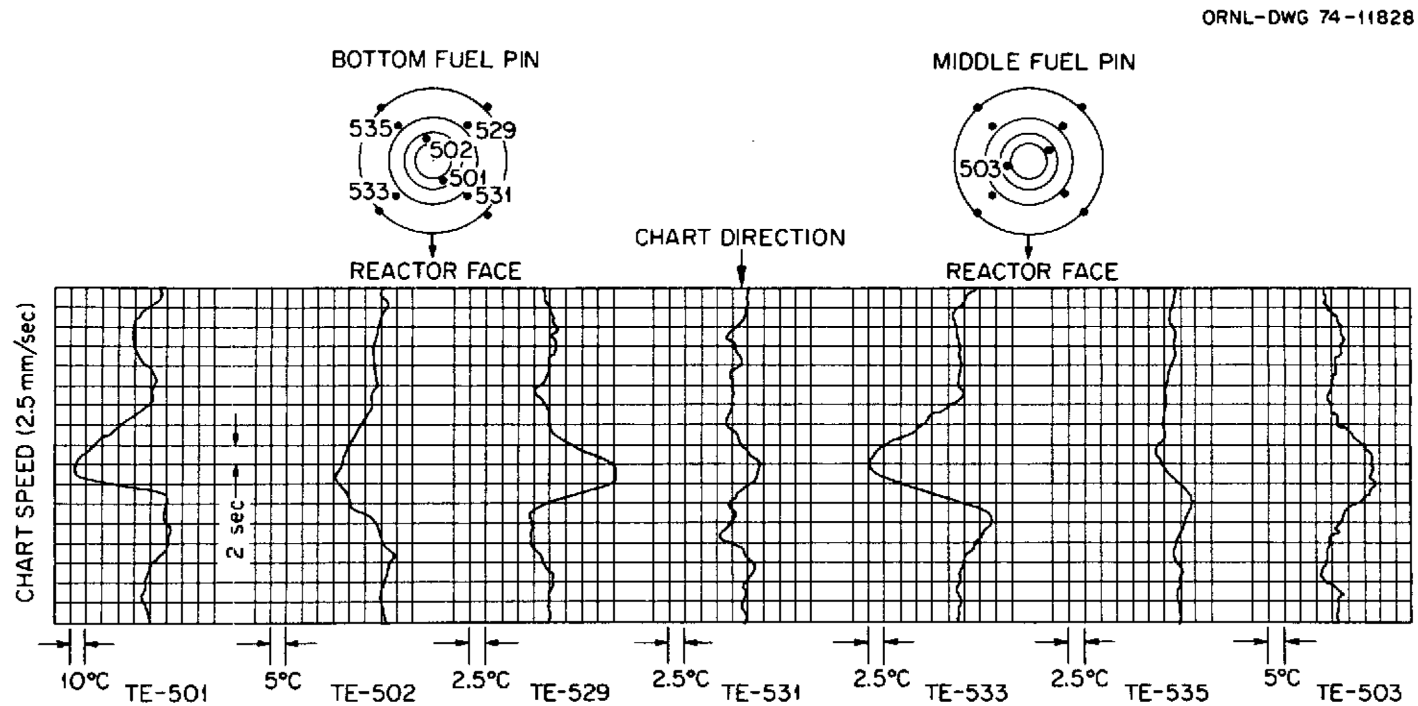

Fig. 20. Typical thermal oscillations taking place in capsule UN-5. Thermocouple locations are shown above recorder chart.

increases rapidly with increase in heat generation rate due to the low thermal conductivity of the UO_2 fuel. Therefore, the capsule was operated at lower than desired temperatures while we attempted to analyze why the observed temperature data was in such poor agreement with design calculations. This observation was especially baffling, since we thought the problem of poor agreement between calculated and observed thermocouple data was due to poor centering of the NaK container and had put in extra effort to assure the centering of the NaK container of UN-6 by adding 12 centering fins to the NaK container and reducing the tolerance between the fins and the primary containment tube.

After extensive analysis of the early operating data, it was determined that the problem was in the assumption that was made for the amount of gamma heat flowing through the calorimeter. Originally, it was assumed that 9% of the heat flowing through the calorimeter could be attributed to gamma heat. However, due to the lower heat rating of UN-6 and the discovery of an error in the gamma heating data that were used, it was determined that 22% of the heat flow should have been attributed to gamma heat. On the basis of this finding, the data for the original insertion were revised, as shown in Fig. 21. This figure shows fairly good agreement between calculated and measured thermocouple data. However, at the higher heat generation rates, we were still operating slightly below desired temperatures. In an effort to raise the cladding temperature without increasing the heat generation rate, the helium in the

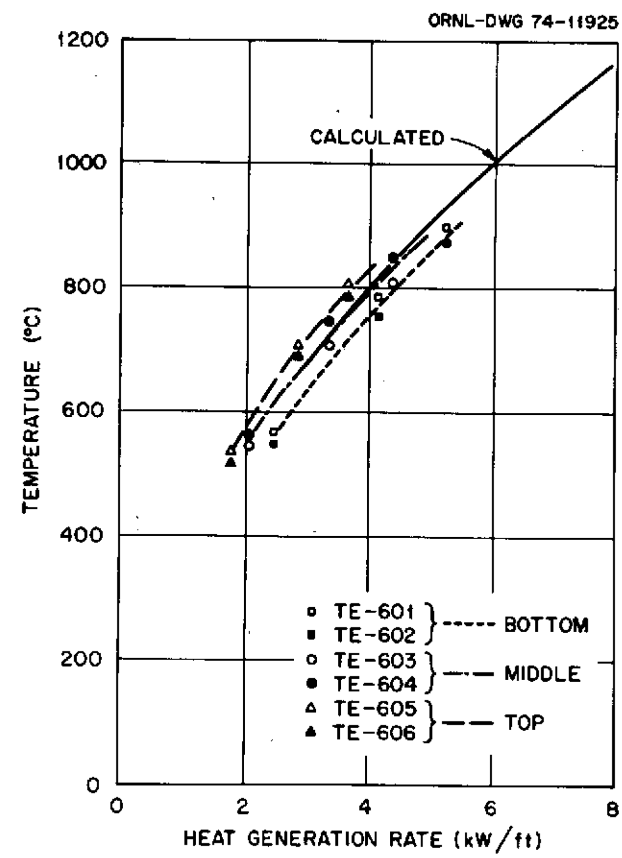

Fig. 21. Comparison of calculated and indicated cladding thermocouple temperature vs heat generation rate for the three fuel pins of capsule UN-6 based on data obtained during initial insertion.

secondary gas region was changed to argon. A comparison of observed thermocouple response to calculated response with argon in the secondary gas region is presented in Fig. 22. A comparison of Figs. 21 and 22 shows that the cladding thermocouple temperature for the bottom fuel pin at a heat generation rate of 5 kW/ft had increased from 860 to 940°C after changing the secondary gas from helium to argon.

As with UN-4 and -5, the criteria for control of this capsule were varied throughout a reactor fuel cycle. The two most important operating criteria for this capsule were that no fuel pin operate with a calculated fuel center-line temperature above 1600°C and that the middle fuel pin operate at an average cladding temperature of 1000°C. We found that we were unable to operate the middle fuel pin at 1000°C without exceeding 1600°C fuel center-line temperature in another pin. Therefore, during the beginning of a fuel cycle, the bottom fuel pin was operated at a cladding temperature of about 1010°C with a fuel center-line temperature of about 1590°C. Later in the fuel cycle, the control would shift to the top fuel pin, which was held at a cladding temperature of about 1030°C with a calculated fuel center-line temperature of about 1550°C. Throughout a fuel cycle, the middle fuel pin operated at an average cladding temperature of between 925 and 960°C.

Apparently the additional centering spacers placed on the NaK container of this capsule prevented movement of the NaK container as was observed in capsules UN-4 and -5. However, we did observe

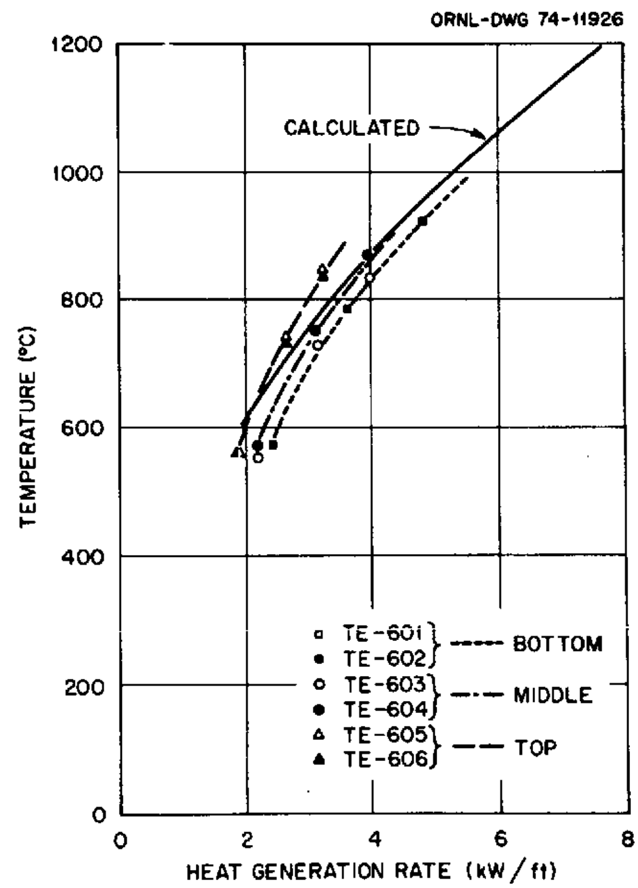

Fig. 22. Comparison of calculated and indicated cladding thermocouple temperature vs heat generation rate for the three fuel pins of capsule UN-6 with argon in the secondary gas region.

thermal oscillations. When the oscillating thermocouples and associated calorimeter thermocouples were placed on an eight-channel Sanborn recorder, we could not find the correlation of thermocouple responses that was reported for capsule UN-5. We attributed the thermal oscillations of UN-6 to thermal convection currents developed in the NaK annulus.

The thermocouple performance in this capsule was by far the best of all three capsules. Only two thermocouples gave any problems at all. Thermocouple TE-601 began to show signs of decreased temperature for a given heat rating after about 900 hr of operation. After about 5600 hr, thermocouple TE-602 failed with an open circuit during cooldown following a reactor shutdown. Upon returning to power, the thermocouple flaw corrected itself, but significantly lower temperatures were indicated for a given heat generation rate.

Three sets of neutron radiographs were also taken of capsule UN-6: one preirradiation, one after 6050 hr of irradiation, and one at the completion of the test. The second and third sets of neutron radiographs showed that the largest single change in appearance of the capsule from its preirradiated condition was in the fuel pellets of the bottom fuel pin, which operated at the highest heat generation rate and therefore had the highest burnup. The fuel pellets in this pin had numerous cracks and the ends of the pellets appeared to have taken on a dished shape. The central hole appeared to have necked down about 0.020 in. at the axial midplane of the fuel stack. With the exception of a few fuel pellet cracks, the other two fuel pins showed no change.

7. POSTIRRADIATION EXAMINATION

The postirradiation examination of these capsules was divided between ORNL and the NASA Plum Brook Reactor Facility Hot Laboratory. Only the disassembly and preliminary examination which was performed at ORNL will be reported here. The more detailed evaluation performed by NASA will be reported elsewhere.

Following completion of the irradiation of these capsules, they were removed to the ORR hot cell, where the lead tubes were cut off above the secondary containment bulkhead. During this operation, great care was taken not to allow air to enter the NaK blanket gas tubes. These tubes were crimped, cut, and sealed with epoxy. After marking the outer containment to maintain orientation with respect to the reactor, the remaining parts of the capsules were moved to the High-Radiation-Level Examination Laboratory (HRLEL), where the fuel pins were recovered.

The procedure developed for recovery of the fuel pins was as follows:

1. remove the primary and secondary containment tubes;
2. visually inspect and make diametral measurements of the NaK container (measurements reported in Appendix E);
3. cut off the bottom of the NaK container and pour the NaK into a container swept with argon;
4. attach an argon supply to one of the NaK blanket gas lines and purge the capsule with argon;
5. immerse the capsule in a tube of mercury, remove the argon supply, and allow the mercury to fill the capsule;
6. after NaK has reacted with mercury, remove the capsule from the mercury, drain the capsule, and purge with argon;
7. immerse the capsule in a second tube of mercury to react any remaining NaK and drain and purge with argon;
8. make a dry rotary cut about 15.5 in. from the bottom of the capsule and pull the bulkhead from the capsule body to withdraw the thermocouples and the fuel pins.

The mercury amalgamation method was used (rather than alcohol) to remove the NaK to minimize the risk of hydrogen embrittlement of the T-111. After the fuel pins were removed from the NaK container, they were again washed in clean mercury; following this last wash, they were found to be coated with a very light white film which was assumed to be oxides of potassium and/or sodium. The pins with no visible cracks were rinsed with distilled water to remove this film and then immediately dried.

Visual examination of the fuel pins revealed that the fuel pins containing 95% dense UN (bottom pin of UN-4 and middle pin of UN-5) had longitudinal cracks that extended over the length of the fuel stack. Figures 23 to 25 present the postirradiation appearance of the fuel pins irradiated in UN-4, -5, and -6 respectively. The two failed fuel pins (12 and 14) are shown in Figs. 23 and 24 respectively. The UO_2 fuel pins from capsule UN-6, Fig. 25, are shown with their cladding thermocouples still attached.

Following visual examination, each fuel pin was weighed and measured diametrally. The diametral measurements were made with a profilometer consisting of opposing dial gages calibrated with a 0.3755-in.-diam stainless steel rod. The measurements were made at 0.5-in. intervals, starting 0.5 in. from the top end and at 0 and 90° orientations. The 0° orientation corresponds to the side of the pin closest to the reactor face. Results of these measurements are presented in Appendix E.

All the fuel pins except pins 12 and 14, which had obvious cladding cracks, were tested with a helium leak detector. Each fuel pin was placed in a vacuum-tight pressure vessel, and the vessel was evacuated and then pressurized with helium to 40 psig for several minutes. The pin was then transferred to another vessel which was evacuated. When the vessel pressure reached an indicated 50 μ, a portion of the gas was bled into the helium leak detector. Two clean polished rods similar in size to the fuel pins were used as "no-leak" standards, and two crimped specimens were used as "known-leak" standards to check the procedure.

Fuel pins 10, 15, and 16 gave slight indications of leaks, but close visual examination revealed no cracks and comparison of pre- and postirradiation fuel pin weights clearly showed that no leaks were large enough to allow NaK to enter the pins.

Following helium leak checking, all the fuel pins and NaK containers were packaged and shipped to NASA for more detailed examination.

ACKNOWLEDGMENT

The author wishes to express his appreciation to all who participated in the fabrication and operation of these experiments. Special thanks are due E. J. Manthos, formerly of the Metals and Ceramics Division of ORNL, who supervised the fabrication of the fuel pins and NaK containers. W. W. Johnston, Jr., Instrumentation and Controls Division, developed the technique for calibrating the cladding thermocouples following brazing operations. The aid of B. Fleischer in the analysis of operating problems was most valuable, and E. D. Clemmer and L. P. Pugh assured the successful operation of the experiments. Special thanks are also due E. M. King and A. A. Walls for supervising the postirradiation examination at ORNL.

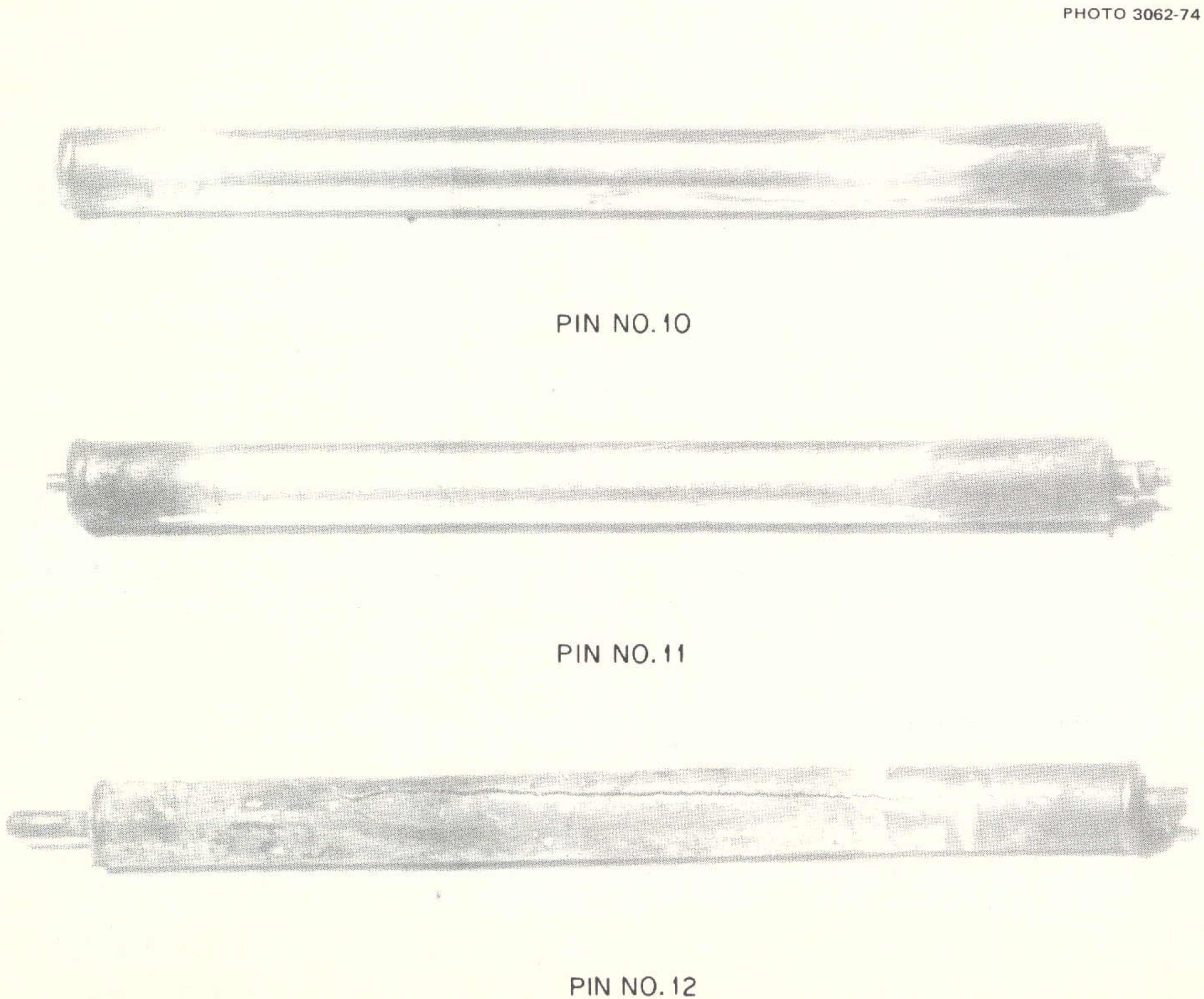

Fig. 23. Postirradiation appearance of fuel pins irradiated in capsule UN-4.

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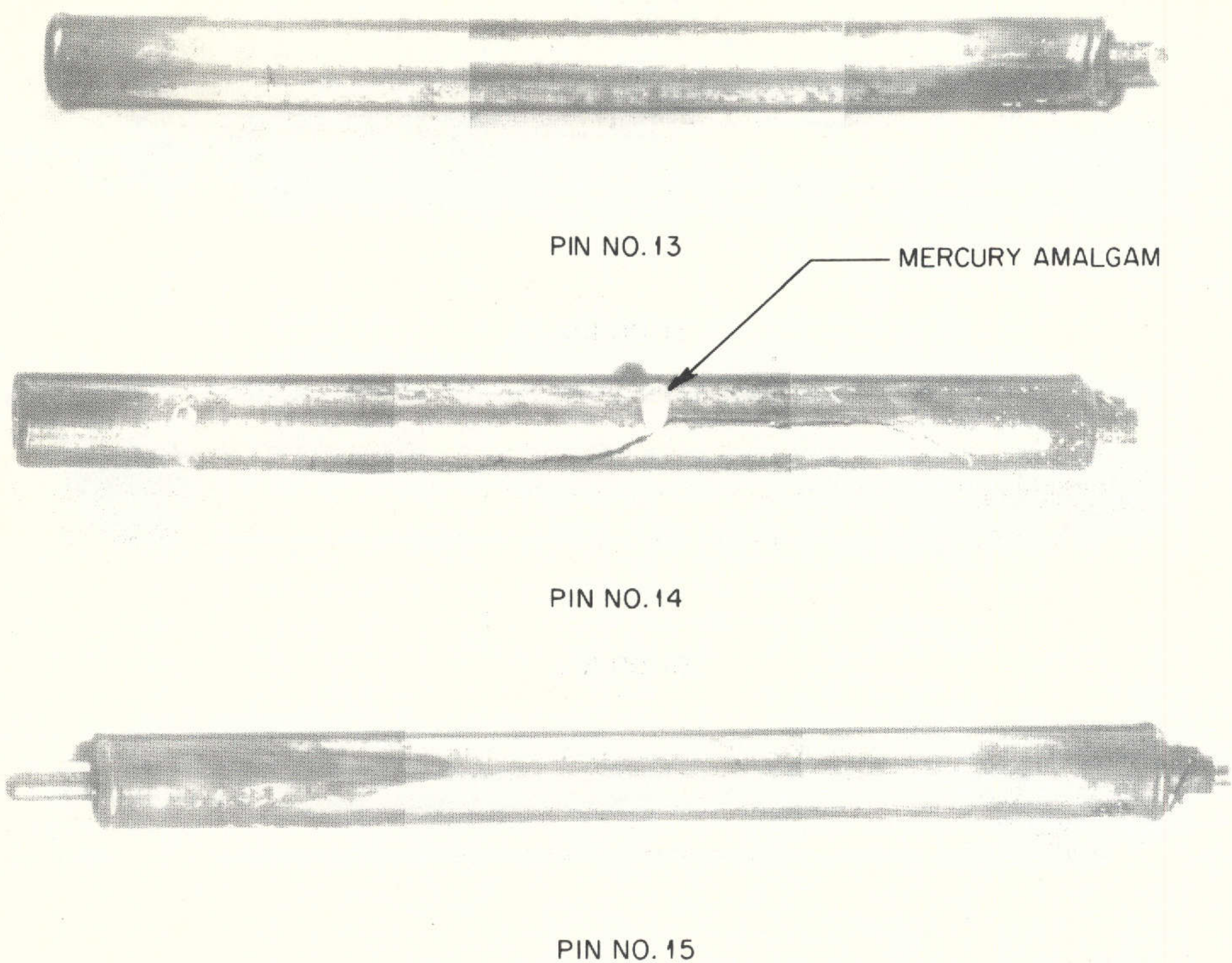

Fig. 24. Postirradiation appearance of fuel pins in capsule UN-5.

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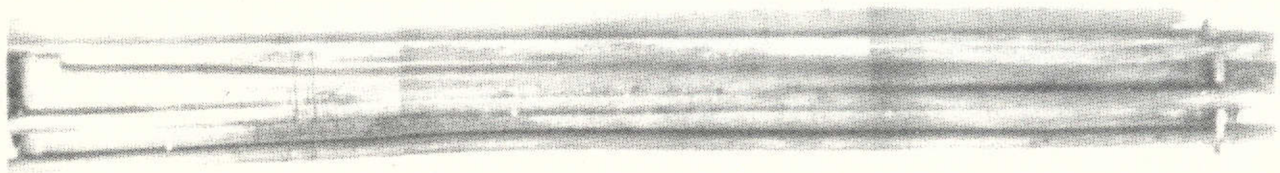
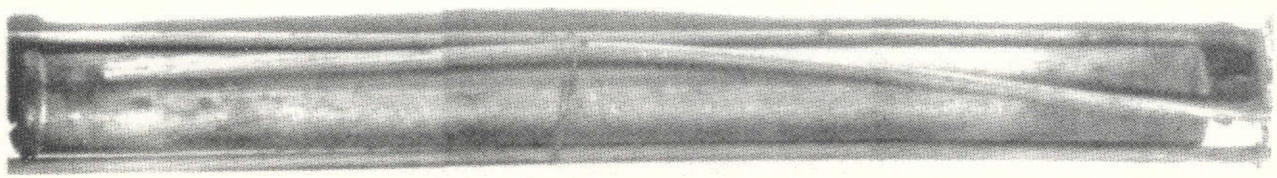


PIN NO. 16



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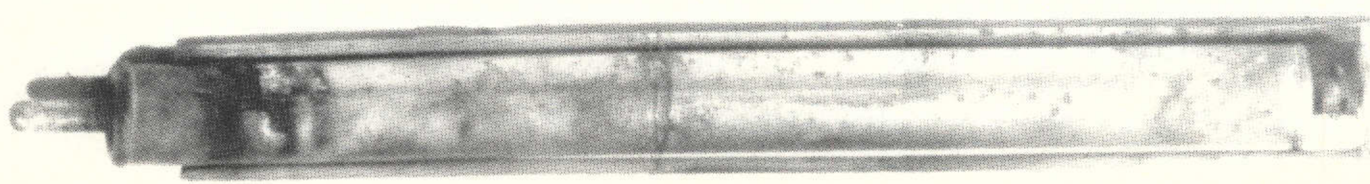

PIN NO. 18

Fig. 25. Postirradiation appearance of fuel pins in capsule UN-6.

APPENDIX A

Table A.1. Description of fuel pins for capsules UN-4, -5, and -6

	Capsule UN-4			Capsule UN-5			Capsule UN-6		
	Pin 10	Pin 11	Pin 12	Pin 13	Pin 14	Pin 15	Pin 16	Pin 17	Pin 18
Position in capsule	Top	Middle	Bottom	Top	Middle	Bottom	Top	Middle	Bottom
Cladding									
Material	T-111	T-111	T-111	T-111	T-111	T-111	Nb–1% Zr	T-111	Nb–1% Zr
Tube No.	4	19	10	6	14	11	12	18	9
OD, in.	0.3720/0.3730	0.3715/0.3720	0.3724/0.3727	0.3729/0.3733	0.3723/0.3732	0.3722/0.3731	0.3739/0.3745	0.3727/0.3729	0.3744/0.3752
ID, in.	0.3174/0.3180	0.3174/0.3179	0.03175/0.03180	0.3174/0.3176	0.3174/0.3180	0.3176/0.3178	0.3172/0.3179	0.3174/0.3178	0.3163/0.3178
Wall thickness, in.	0.0268/0.0283	0.0267/0.0279	0.0269/0.0287	0.0271/0.0280	0.0270/0.0282	0.0266/0.0288			
Weight, g	37.053	36.690	37.356	37.557	37.265	37.381	19.407	37.340	19.596
Cladding liner									
Material	Tungsten	Tungsten	Tungsten	Tungsten	Tungsten	Tungsten	Tungsten	Tungsten	Tungsten
Liner No.	2	12	8	16	19	15	4	13	20
OD, in.	0.3159/0.3164	0.3160/0.3162	0.3162/0.3164	0.3160/0.3162	0.3160/0.3162	0.3161/0.3163	0.3161/0.3163	0.3160/0.3161	0.3161/0.3162
Fuel pellets									
Material	UN	UN	UN	UN	UN	UN	UO_2	UO_2	UO_2
^{235}U enrichment, %	19.86	10.96	10.96	19.86	10.96	10.96	10	10	8
Density, % theoretical	85.82/86.03	83.94/84.78	93.85/94.27	85.54/86.73	93.85/94.28	83.94/84.78	95.26/95.62	95.26/95.44	95.80/96.08
Stack length, in.	3.0009	3.0018	2.9989	2.9998	3.0008	3.0002	3.0000	3.0016	3.0009
Weight, g	44.9204	44.0493	44.9044	44.9513	44.9927	44.0773	35.475	35.478	35.647
OD, in.	0.3072/0.3080	0.3071/0.3077	0.3072/0.3078	0.3070/0.3080	0.3075/0.3077	0.3072/0.3078	0.3080	0.3080	0.3080
ID, in.			0.0895/0.0905		0.0890/0.0905		0.084	0.084	0.084
Stack No.	533-1	B4-2	535-1	533-3	R-535-2	B4-3	10-1	10-3	8-1
Number of pellets	8	9	8	8	8	9	10	10	10
Weight of finished fuel pin, g	102.444	100.705	103.286	102.862	102.488	102.780	69.453	93.455	70.307

Table A.2. Isotopic and chemical analysis of UN pellets used in capsules UN-4 and -5

	Fuel pin number		
	10, 13	12, 14	11, 15
Pellet batch	533	535	B-4
^{233}U, wt %	<0.0005	<0.0005	<0.0005
^{234}U, wt %	0.131	0.099	0.090
^{235}U, wt %	19.86	10.96	10.96
^{236}U, wt %	0.122	0.043	0.043
^{238}U, wt %	79.89	88.90	88.90
N, wt %	5.38/5.37	5.41/5.46	5.49/5.48
U, wt %	94.40/94.41	94.41/94.42	94.36/94.34
O, ppm	950,980,1010	900,970	1270,1330
C, ppm	330,330	280,380	120,170
B, ppm	0.4	1	0.4
Ca, ppm	50	20	0.5
Cb, ppm	0.1	<0.1	0.3
Co, ppm	<0.1	<0.1	<0.1
Cr, ppm	0.7	0.7	2
Cu, ppm	1	1	0.4
Fe, ppm	7	7	2
K, ppm	5	0.2	0.2
Mg, ppm	3	1	0.3
Mn, ppm	0.2	0.2	0.1
Mo, ppm	1	4	1
Na, ppm	3	0.1	0.1
Ni, ppm	1	1	3
P, ppm	0.1	1	<0.1
Si, ppm	7	0.7	20
Ta, ppm	2	0.7	2
V, ppm	0.1	0.2	0.1
W, ppm	0.7	2	0.7
Zr, ppm	0.7	7	0.7
Th, ppm	<0.1	<0.1	0.3
Re, ppm	0.3	<0.1	0.3
S, ppm	10	3	3

Table A.3. Isotopic (wt %) and chemical (ppm) analysis of UO_2 pellets used in capsule UN-6

	Fuel pin numbers	
	17	16, 18
Pellet batch	8	10
^{233}U	<0.0005	<0.001
^{234}U	0.059	0.075
^{235}U	8.27	10.28
^{236}U	0.031	0.040
^{238}U	91.64	89.60
O/U	2.0003	2.0005
C	45	25
Al	50	50
As	5	2
B	0.7	0.7
Ba	0.9	0.9
Be	5	20
Ca	80	200
Cb	0.6	0.6
Co	0.4	0.4
Cr	30	30
Cu	20	60
Fe	600	2000
K	20	20
Li	0.1	0.4
Mg	5	15
Mn	1	10
Mo	200	8
Na	1	1
Ni	50	150
P	2	6
Sb	10	10
Si	100	1000
Sn	2	7
Sr	0.5	0.5
Ta	100	100
Ti	2	2
Th	15	15
V	0.1	0.3
W	400	40
Zn	0.5	0.5
Zr	1	1
Re	200	
S	15	15

Table A.4. Summary of NDT inspection performed on T-111 fuel pin tubing

Tube No.	Dimensional inspection: OD, min/max (in.)	Dimensional inspection: ID, min/max (in.)	Dimensional inspection: Wall thickness, min/max (in.)	Dimensional inspection: Plug gage inspection	Surface condition: Visual inspection	Surface condition: Fluorescent penetrant indications: Number	Surface condition: Fluorescent penetrant indications: Location[a]	Wall defects[b]: X-ray radiography	Wall defects[b]: Pulse echo ultrasonics: Number	Wall defects[b]: Pulse echo ultrasonics: Size	Wall defects[b]: Pulse echo ultrasonics: Location	Maximum usable length of tubing (in.)	Disposition
1	0.3721 0.3725	0.3171 0.3175	0.0264 0.0283	Passed	Passed	0		Passed	1	S	3.0	3.0	Weld specimens
2	0.3716 0.3729	0.3170 0.3174	0.0274 0.0284	Passed	Passed	1	0.5	Passed	2	L, S	0.5, 2.5	3.5	UN-4, -5 thermal simulation pin
3	0.3718 0.3722	0.3176 0.3180	0.0272 0.0281	Passed	Passed	0		Passed	2	L, E	3, 4.5	30	UN-4, -5 thermal simulation pin
4	0.3720 0.3730	0.3174 0.3180	0.0269 0.0282	Passed	Faint circumferential tool mark on ID	0		Circumferential tool mark at 4 in.	0			6.0	UN-4 top pin
5	0.3720 0.3730	0.3174 0.3180	0.0270 0.0286	Passed	Passed	0		Passed	1	E	2.0	4.0	Weld specimen
6	0.3729 0.3733	0.3174 0.3176	0.0271 0.0288	Passed	Small gage on OD, 4.7 in.	0		Passed	0			4.7	UN-5 top pin
7	0.3171 0.3174	0.3171 0.3174	0.0272 0.0286	Passed	Numerous ID and OD defects	0		Numerous defects	2	E, L	0.5, 4.7	3.0	UN-4, -5 thermal simulation pin
8	0.3715 0.3723	0.3172 0.3180	0.0261 0.0288	Passed	Numerous ID tool marks	0		Numerous defects	4	S, S, S, S	1–3.5	0	UN-4, -5 thermal simulation pin
9	0.3719 0.3725	0.3174 0.3183	0.0249 0.0306	Did not pass through tube	Small OD gages at 1 and 2 in.; ID tool marks corresponding to x ray	0		Circumferential tool marks from 3 to 6 in.	1	E	4.0	2.5	UN-4, -5 thermal simulation pin
10	0.3724 0.3727	0.3175 0.3178	0.0260 0.0287	Passed	Faint circumferential tool mark on ID	0		Passed	0			6.0	UN-4 bottom pin
11	0.3722 0.3731	0.3176 0.3178	0.0266 0.0288	Passed	Faint circumferential ID tool marks at 5 in.	0		Faint circumferential tool marks at 5 in.	2	S, E	4.5, 5.0	4.5	UN-5 bottom pin
12		0.3173 0.3177	0.0268 0.0294	Passed	Faint circumferential ID tool marks	0		Passed	1	L	1.0	5.0	Not used
13	0.3723 0.3730	0.3174 0.3178	0.0256 0.0296	Did not pass through tube	Circumferential ID tool marks; OD gage at 1.5 in.	0		Circumferential tool marks	5	S	Scattered along tube length	0	UN-6 thermal simulation pin
14	0.3723 0.3732	0.3174 0.3178	0.0270 0.0282	Passed	Longitudinal ID scratches, 5 to 6 in.	0		Passed	0			5.0	UN-5 middle pin
15	0.3724 0.3729	0.3175 0.3179	0.0264 0.0285	Passed	Circumferential OD tool mark at 2 in.; OD gage at 4.5 in.	0		Circumferential tool mark at 2 in.	3	S, E, E	1, 3.7, 4.2	1.5	Weld specimens
16	Used as standard for pulse echo ultrasonics												
17		0.3174 0.3178	0.0271 0.0282	Passed	Numerous OD gages	1	3.5	Circumferential tool mark at 3 in.	4	L, VL, VL, S	3, 3.5, 4, 4.2	1.5	Not used
18	0.3727 0.3729	0.3174 0.3178	0.0258 0.0295	Passed	Passed	0		Passed	0			0	Un-6 middle pin
19	0.3715 0.3720	0.3174 0.3179	0.0268 0.0277	Passed	Passed	0		Passed	0			6.0	UN-4 middle pin

[a] Distance measured from numbered end of tube.

[b] Legend: VL = very large, larger than the reference; L = large, slightly larger than the reference; E = equal, equal to the reference; and S = small, smaller than the reference.

Table A.5. Summary of NDT inspections performed on Nb–1% Zr fuel pin tubing

Tube No.	Vendor	Dimensional inspection				Surface condition		Wall defects			
		OD, min/max (in.)	ID, min/max (in.)	Wall thickness, min/max (in.)	Plug gage inspection	Visual inspection	Number of fluorescent penetrant indications	X-ray radiography	Pulse echo ultrasonics: Transverse	Pulse echo ultrasonics: Longitudinal	Disposition
1	NASA-PUNL	0.3745 0.3750	0.3175 0.3182	0.0292 0.0302	Passed	Longitudinal OD scratches	0	Passed	Passed	Passed	Not used
2	NASA-PUNL	0.3735 0.3742	0.3179 0.3182	0.0265 0.0282	Passed	Longitudinal OD scratches Circumferential ID scratches	0	Passed	Passed	Passed	Not used
3	NASA-PUNL	0.3745 0.3752	0.3185 0.3188	0.0253 0.0294	Passed	Longitudinal ID scratches	0	Passed	Reject	Passed	Not used
4	NASA-PUNL	0.3740 0.3749	0.3184 0.3188	0.0254 0.0288	Passed	Passed	0	Passed	Reject	Passed	Not used
5	NASA-PUNL	0.3750 0.3755	0.3182 0.3185	0.0266 0.0292	Passed	Passed	0	Passed	Passed	Passed	Not used
6	NASA PUNL	0.3746 0.3753	0.3186 0.3189	0.0260 0.0287	Passed	Passed	0	Passed	Reject	Passed	Not used
7	GE-NSP	0.3762 0.3765	[a]								
8	GE-NSP	0.3748 0.3753	0.3150 0.3179	0.0268 0.0301	Passed	Deep pit on OD	0	Passed	Reject	Passed	Not used
9	GE-NSP	0.3744 0.3752	0.3163 0.3178	0.0262 0.0307	Passed	Dents on OD	0	Passed	Passed	Passed	UN-6 bottom pin
10	GE-NSP	0.3743 0.3752	[b]								Not used
11	GE-NSP	0.3744 0.3749	0.3166 0.3178	0.0248 0.0308	Passed	OD and ID scratches	0	Passed	Passed	Passed	UN-6 thermal simulation for bottom pin
12	GE-NSP	0.3739 0.3748	0.3172 0.3179	0.0258 0.0302	Passed	OD gouges	0	Passed	Passed	Passed	UN-6 top pin
13	GE-NSP	0.3741 0.3748	0.3175 0.3179	0.0246 0.0302	Passed	OD dents	0	Passed	Passed	Passed	UN-6 thermal simulation for bottom pin

[a] Rejected – original ID was oval and no attempt was made to machine tube.
[b] Rejected – tube bent to 0.012 in. TIR; scratched on ID.

Table A.6. Comparison of oxygen, nitrogen, hydrogen, and carbon analyses for T-111 tubing

Analyst	Tubing No.	Sample No.	Chemical content (ppm)			
			Oxygen	Nitrogen	Hydrogen	Carbon
Ledoux	WE1		26	35	3.9	47
Ledoux	WE1		29	34	4.6	40
ORNL	WE1	A-1, A-2	36	23	3	45
ORNL	WE1	B-1, B-2	30	22	<1	29
ORNL	WE1	C-1, C-2	48	18	<1	32
Ledoux	WE2		19	18	43	30
Ledoux	WE2		18	14	49	37
ORNL	WE2	D-1, D-2	29	14	1	35
ORNL	WE2	E-1, E-2	23	8	<1	40
ORNL	WE2	F-1, F-2	23	10	<1	53
ORNL	A	G-1, G-2	31	23	<1	32

Table A.7. Chemical composition of Nb–1% Zr tubing

Element	Composition (ppm by weight)	
	NASA-PNUL tubing	GE-NSP tubing
Ag	20	20
Al	0.9	3
B	0.4	0.1
C	1100	57
Ca	0.4	0.4
Co		0.2
Cr	2	6
Cu	30	100
Fe	6	20
H_2	4	12
K	0.4	0.4
Mg	8	8
Mn	0.2	0.2
Mo	≤1	≤1
N_2	37	8
Na	<0.7	<0.7
Ni	0.3	25
O_2	12	26
Si	2	60
Ta	60	60
Ti	30	300
V	<0.2	<0.2
W	20	20
Zr	0.94[a]	0.80[a]

[a]Weight percent.

APPENDIX B

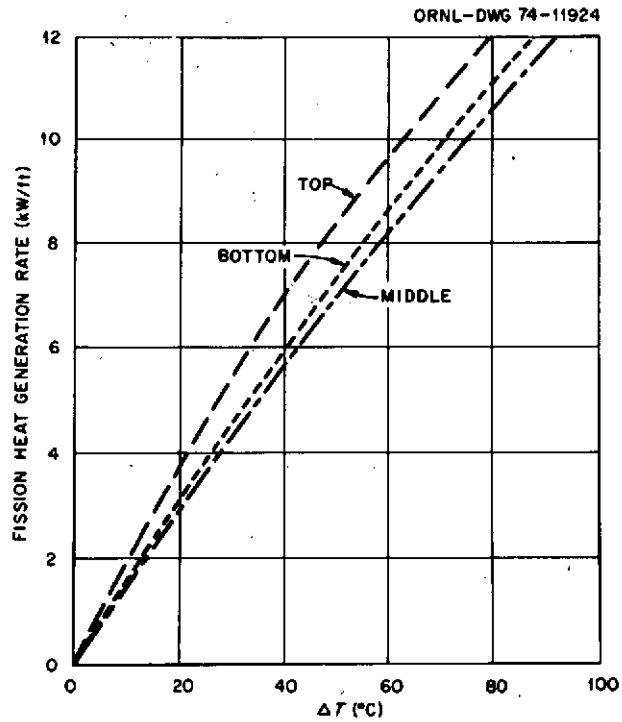

Fig. B.1. Calibration curve for calorimeter of capsule UN-4. Fission heat generation rate vs temperature difference between the inner and outer thermocouples at the axial midplane of each fuel pin.

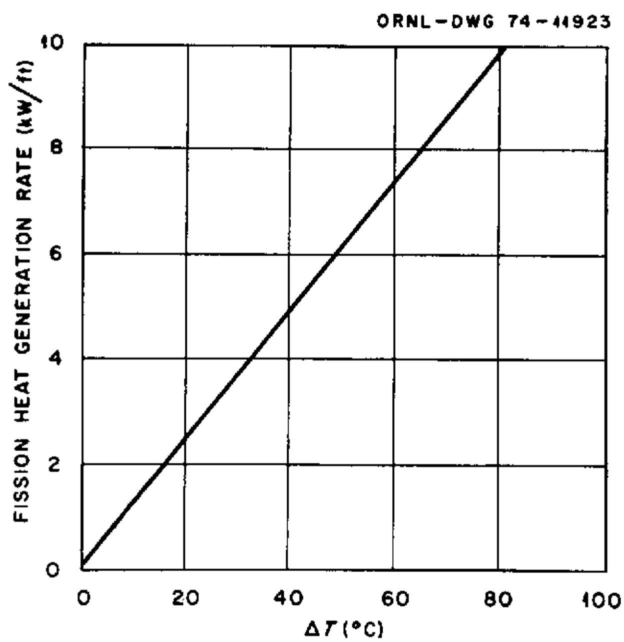

Fig. B.2. Calibration curve for calorimeter of capsule UN-5. Fission heat generation rate vs temperature difference between inner and outer thermocouple at the axial midplane of each fuel pin.

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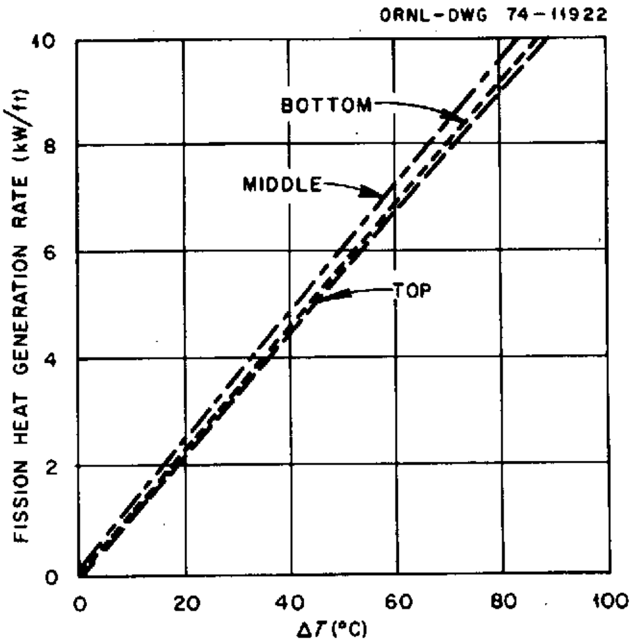

Fig. B.3. Calibration curve for calorimeter of capsule UN-6. Fission heat generation rate vs temperature difference between inner and outer thermocouples at the axial midplane of each fuel pin.

APPENDIX C

Fuel Cycle Technology	**Procedure No.** MET-FCT-PP-18
Metals & Ceramics Division	**Revision No.** 0
OAK RIDGE NATIONAL LABORATORY	**Date** February 26, 1970
Oak Ridge, Tennessee	**Page** 1 **of** 9

PROCESS PROCEDURE

TITLE: Fuel Pin Fabrication — Capsules UN-4 and UN-5

Prepared by: E. J. Manthos

Approved by: T. N. Washburn *T N Washburn*

DQAC Approval: W. J. Werner *W J Werner*

1. Scope

This procedure describes the procedure to be followed in assembly, fabrication, and inspection of fuel pins for capsules UN-4 and UN-5. Ten fuel pins will be fabricated: six for irradiation testing, and four for out-of-pile thermal simulation testing.

2. Reference Drawing

M-10557-Rm-016 E Rev. 0.

3. Pins to be Fabricated

Part Number	Quantity	UN Pellet Density	Enrichment ^{235}U
6-11 (same as 6-12)	3	85% T.D.	20%
6-14 (same as 6-18)	4	85% T.D.	11%
6-17 (same as 6-15)	3	95% T.D.	11%

4. Components

All fuel pin hardware components are fabricated and inspected per MET-FCT-PP-17. Uranium nitride fuel pellets are fabricated to specification MET-FCT-MS-2.

5. Weld Bottom End Plug

The bottom end plug shall be welded in an inert atmosphere glove box by the Welding and Brazing Group per procedure MET-FCT-PP-19. Do not wire brush weld region after welding.

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5.1 The bottom end plug and T-111 tube will be weighed before and after welding. Record weight below.

T-111 tube No.______________, Weight ______________g

Bottom end plug part No. ______________, weight ________g

Total weight after welding ______________g

5.2 This weld shall be helium leak tested in accordance with MET-FCT-PP-23. Maximum acceptable leak rate shall be 2×10^{-9} cm^3/sec.

5.3 This weld shall be subjected to penetrant inspection in accordance with MET-NDT-4.

5.4 The bottom end plug weld shall be x rayed, three positions, 60° apart in accordance with MET-FCT-PP-25.

6. Fuel Pin Assembly (Vertical Position)

6.1 Recheck ID of T-111 cladding with go-no-go plug gage. Plug should slide in and out of cladding freely.

Insert welded tube into plastic sleeving sealed at one end; tape sleeving to tube so that tape is flush with top end of tube.

6.2 Weigh a tungsten liner, Part No. 6-11-6.

Weigh = ______________g

Insert tungsten liner into T-111 cladding until liner bottoms out on end plug.

Top end of liner should be 0.250 in. below the top end of cladding. Measure this distance and record ___________in.

6.3 Weigh flat tungsten washer without outer hole (Part No. 6-11-10),

Weigh = ______________g

Insert washer into cladding. Be sure washer is lying flat on end plug.

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6.4 Weigh one spherical spacer (Part No. 6-11-3).

Weight = ______________ g

Insert spherical spacer into cladding with spherical face against end plug.

6.5 Weigh 0.003-in.-thick flat washer with center hole (Part No. 6-11-2).

Weight = ______________ g

6.6 Weigh two spherical spacers (Part No. 6-11-3).

No. 1 weight = ______________ g

No. 2 weight = ______________ g

Insert two spacers into cladding. First spacer should have open face towards end plug. Second spacer should have open face away from end plug. (Spherical faces should be touching.) Insert Spacer No. 1 first.

6.7 Weigh 0.005-in. flat washer with center hole (Part No. 6-11-4).

Weight = ______________ g

Insert flat washer into cladding.

6.8 Weigh and measure length of tubular tungsten spacer

(Part No. 6-11-9). Length = ______________ in.

Weight = ______________ g

6.9 Obtain UN pellets. Record number of pellets, stack length, pellet density, enrichment, and batch or Run Number below.

Number of pellets = __________ Stack length = __________

Pellet Density = __________ % Enrichment = __________

Batch or Run No. = __________ Total weight = __________

Attach all other pertinent data and information to the last sheet in this procedure.

6.10 Insert UN pellets, one at a time, in the order existing in the pre-assembled fuel column stack. (Each pellet has been measured and weighed and will be measured and weighed after irradiation testing. Do not lose position identification.) Dimension from top of fuel column to end of cladding should be 0.751 in.; check and record. Void length = ______________ in.

6.11 Decontaminate top 3/8 in. of tubing ID and OD.

The ID and perhaps the cladding OD were probably contaminated with UN during loading of the fuel pellets. If this contamination is not removed prior to welding, the weld region will be contaminated.

Use the following procedures to decontaminate the top 3/8 in. of the tubing.

6.11.1 Inside Diameter

6.11.1.1 Dampen a clean cotton swab in alcohol. Remove excess alcohol by rolling swab over a clean wipe. Wipe top 3/8 in. of tubing ID out by rolling swab around in tubing. Do not make more than one pass with swab. Make sure that alcohol does not run down on UN pellets. Measure activity of swab with alpha probe. If swab probes less than 100 dpm α, wipe out top 3/8 in. of ID with a dry swab and probe. If swab probes less than 100 dpm α, the ID is clean. Proceed to decontamination of OD. Make sure there are no cotton fibers in capsule.

6.11.1.2 If swab probes greater than 100 dpm α, repeat step "6.11.1.1" until a damp swab and a dry swab read less than 100 dpm α. If activity does not decrease, contact project engineer for further instructions.

6.11.2 Outside Diameter

6.11.2.1 Remove tape and plastic sleeving from OD of tubing. Probe OD surface with alpha probe. Wipe off tape residue with acetone wipe, followed by alcohol wipe. Probe surface. If activity is less than 100 dpm α, the OD is clean. If greater than 100 dpm α, use alcohol wipes to decontaminate. If unsuccessful, contact project engineer.

6.11.2.2 Wipe off top surface of tube with paper smear. If smear is less than 100 dpm α, the top is clean. Use damp alcohol wipes to decontaminate top if smears record greater than 100 dpm α. If unsuccessful, contact project engineer for further instructions.

Before proceeding to step 6.12, engineer in charge of project will inspect ID and OD for cotton fibers and any traces of alcohol.

Engineer Approval to Proceed

Name: ______________________________

Date: ______________________________

6.12 Weigh tubular tungsten spacer (Part No. 6-11-9) and record.

Weight = ____________________g

Insert spacer into cladding.

6.13 Weigh 0.005-in.-thick flat washer (Part No. 6-11-2) with center hole and record.

Weight = ____________________g

Insert washer into cladding.

6.14 Weigh two spherical spacers (Part No. 6-11-3) and record weight.

No. 1 weight = ________________________g

No. 2 weight = ________________________g

Insert the two spherical spacers so that open faces are towards tube ends and spherical faces are touching. Insert Spacer No. 1 first.

6.15 Weigh 0.003-in.-thick flat washer with center hole (Part No. 6-11-2).

Weight = ________________ g

Insert into cladding.

6.16 Weigh spherical spacer (Part No. 6-11-10)

Weight = ________________ g

Insert spherical spacer into cladding with spherical face towards top end of fuel pin.

6.17 Weigh flat tungsten washer without center hold (Part No. 6-11-10).

Weight = ________________ g

Insert washer into cladding.

The distance from the flat washer to top end of tube should be 0.250 in. Measure and record this distance.

Void length = ________________ in.

6.18 Weigh the loaded fuel pin invertical position and compare this weight to the sum of the component weights.

Step	Item	Weight
5.1	Weight of tube and end plug	____
6.2	Liner, Part No. 6-11-6	____
6.3	Washer, Part No. 6-11-10	____
6.4	Spherican Spacer, No. 6-11-3	____
6.5	Washer, No. 6-11-2	____
6.6	Spherical Spacer No. 1, 6-11-3	____
	Spherical Spacer No. 2, 6-11-3	____
6.7	Washer, No. 6-11-4	____
6.8	Spacer, No. 6-11-9	____
6.9	Pellets, total weight	____
6.12	Spacer, No. 6-11-9	____
6.13	Washer, No. 6-11-4	____
6.14	Spherical Spacer No. 1, 6-11-3	____
	Spherical Spacer No. 2,	____
6.15	Washer, No. 6-11-2	____
6.16	Spherical Spacer, No. 6-11-3	____
6.17	Washer, No. 6-11-10	____
	Sum	____
	Actual weight	____
	Difference	____

6.19 Place stopper in end of tube. Maintain fuel pin in vertical position during transfer to welding operation.

7. Welding of Top End Plug

7.1 Select a top end plug and weigh it.

Weight = ____________

7.2 Transfer end plug and fuel pin into welding glove box. Fuel pin should be kept in vertical position.

7.3 Remove plastic stopper from end of tube. Install and position tube in chuck.

7.4 Evacuate and purge weld box with helium and weld end plug per procedure MET-FCT-PP-19.

7.5 Visually inspect weld. Do not wire brush weld.

7.6 Smear weld region and fuel pin (two separate smears). Have Health Physics count both smears for α and β,γ. Store fuel pin in glass container and capped metal pipe.

7.7 Helium leak test fuel pin in accordance with MET-FCT-PP-23. Maximum accptable leak rate shall be 2×10^{-9} cm^3/sec.

7.8 Subject the weld region to fluorescent penetrant inspection in accordance with MET-NDT-4.

7.9 The top end plug weld shall be x-ray radiographed three positions, 60° apart in accordance with MET-FCT-PP-25.

7.10 If the fuel pin passes inspections in Steps 7.5, 7.6, 7.7, 7.8, and 7.9, it is ready to be numbered as shown in Dwg. M-10557 Rm-016 E.

7.11 Weigh fuel pin.

Weight = ____________.

8. Cleaning

The fuel pin shall be cleaned by the following procedure.

8.1 Degrease with acetone followed by ethyl alcohol.

8.2 Pickle with nitric-hydrofluoric-sulfuric acid solution nominally 20, 15, 10% balance water by volume. Time 1 to 2 minutes.

8.3 Rinse as follows (this is the most important step since pickling residues can cause surface contamination or degas severely on heating).

8.3.1 Fast transfer from pickle bath to rinse without any surface drying of pickle solution.

8.3.2 Thirty seconds boiling distilled water.

8.3.3 One minute flowing cold water.

8.3.4 Five minutes boiling distilled water.

8.3.5 Fast rinse in ethyl alcohol.

8.3.6 Hot air flash dry.

8.3.7 Store in clean containers, tissue, etc., glass containers preferred.

8.4 Pin shall be handled with clean cotton gloves only, from this point on.

9. Heat Treatment

9.1 The fuel pins shall be heat treated for 1 hr at 2400°F in a vacuum of 10^{-5} torr. Each pin shall be wrapped in a layer of T-111 foil during heat treatment.

9.2 At least two pieces of T-111 tubing shall be wrapped in T-111 foil and heat treated at the same time as the fuel pins. One section will be chemically analyzed and the other will be examined metallographically.

10. Fuel Pin Radiography

The entire length of the fuel pin will be x rayed in two positions, 90° apart as per MET-FCT-PP-25. These x-ray films will be viewed carefully to insure proper location and orientation of internal components. The index point or 0° mark shall be the etched fuel pin number.

11. Dimensional Inspection

11.1 The fuel pin diameter will be measured at 0 to 90° every inch. The scribed capsule number will be the 0° index mark. Use MET-FCT-PP-23 as a guide.

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11.2 The overall length of each fuel pin will be measured from weld head to weld head at two locations 90° apart. Record the lengths below. Use MET-FCT-PP-23 as a guide.

0° = __________ in.

90° = __________ in.

12. Hot Cell Inspections

If possible the fuel pins will be inspected at HRLEL with out-of-cell equipment which has been correlated with in-cell equipment.

13. Photography

The fuel pins will be photographed in two positions, 90° apart, in the same orientation used during x-ray exposure of paragraph 10 above.

14. Cleaning

Clean in acetone followed by alcohol, dry with a hot air gun.

15. Fuel Pin Weight

Weigh fuel pin to ± 0.001 g and record.

Weight __________ g

16. Storage

The fuel pins will be stored in glass until released for capsule assembly.

APPENDIX D

ENGINEERING SPECIFICATION REACTOR DIVISION Oak Ridge National Laboratory UNION CARBIDE CORPORATION Oak Ridge, Tennessee	Spec. No. M-10557-RM-001-S-0 Date: January 13, 1970 Rev. No. 1 Rev. Date: November 20, 1970 Page 1 of 10

SUBJECT: ASSEMBLY PROCEDURE - ORR NASA UN-4, 5 & 6 CAPSULE IRRADIATION TEST

Submitted: *APMarquardt* Accepted: *[signature]* Approved: *R. R. [signature]*

I. SCOPE

This procedure lists each step of assembly in a proposed order which is considered to yield, with the minimum assembly time, a finished subassembly with the required accuracy and tightness.

II. REFERENCES

A. Drawings

1. D-001, Parts List
2. E-002, Assembly
3. E-003, Capsule & Fuel Element Assembly
4. D-004, Information Assembly
5. E-005, Details - Lead Tubes
6. D-006, Bulkhead Braze Detail
7. E-007, Details
8. E-008, Thermocouple Lead Tube Subassembly
9. E-009, Fuel Element Details
10. D-011, Elbow, Weldment
11. E-012, Details
12. E-013, Zr-2 Weldment & Details
13. D-014, Details
14. D-015, Support Bracket at Grating
15. E-016, Fuel Element Subassembly
16. D-040, NaK Vessel Details
17. E-10440-R-001, Mockup for Calibration (Ref.)
18. C-050, Test Plug

B. Weld Specifications

1. WPS-302
2. PS-52

C. Inspection Specifications

1. MET-WR-201
2. MET-WR-204
3. MET-NDT-4

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III. CLEANLINESS

Use white gloves, changing frequently, during assembly of fuel capsule. All parts shall be kept free of oil, grit, chips and other contaminants. Gases used for cleaning, blanketing, and pressurizing shall be of purity acceptable to the Project Engineer. Normal building compressed air supply shall not be used for cleaning or drying operations. Instrument air may be used when of proven cleanliness. Use acetone for final cleaning. NOTE: Special care must be taken with the fuel can to insure that no damage is incurred during handling. Any scratches or other marring of the surface of the fuel element must be reported to the Project Engineer.

IV. DEVIATIONS

Deviations from this specification and from the drawings must be approved by the Project Engineer. Record all deviations in experiment log book. As improvements are developed in use, transmit information to the Design Engineer for incorporation.

V. THERMOCOUPLES

A. Leak Check

Leak checking of thermocouple sheaths is to be accomplished by applying helium externally. If sheathed thermocouples must be heated for outgassing, temperature shall be limited to 500°F.

B. Crossed Alloy Check

With continuity established through thermocouple junction and a potentiometer between external leads, check for absence of potential change as each extension junction is separately heated with soldering iron, gun or other suitable heat source. This test is to be performed at any joining of thermocouple wires or extension whether as repair or as a specified part of procedure.

VI. LEAK DETECTOR REQUIREMENTS

Leak rate values stated in the body of this specification are based on readings of a helium leak detector calibrated to agree with at least one standard leak and adjusted and operated at the maximum sensitivity of the machine. Meter readings shall be approximately 200 units for a 2.0×10^{-9} cc/sec std leak or numerically equivalent for leaks of different value. When using "Sniffer," detector shall be throttled only at probe valve and shall be operated at pressure of maximum sensitivity.

VII. RECORD

Maintain an experiment log book with each experiment or group of experiments, noting compliance with or deviation from this procedure as well as all other pertinent data.

VIII. ASSEMBLY SEQUENCE

Item numbers referred to in the following steps are those shown on E-002 unless otherwise noted. Steps 1 through 6 are subassemblied and can be made at any time in any sequence.

Step 1. Complete thermocouple lead tube subassembly (9) as shown on E-008, leaving out neutron absorber (9-5).

Step 2. Weld adapter (10) to tube (3) with Weld No. 3, E-002.

Step 3. Install nut (15) on adapter (14), join adapter, flexible hose (17), pinch valve facility tube (24), and reducer (23) with Welds No. 24, 19, and 9, and inspect (Dwg. E-002).

The following steps are shown on D-040 (NaK vessel), unless otherwise stated:

By M & C

Step 4. Weld sheet (6-2-3) to cap (6-2-2 UN-4, UN-5) or (6-2-4 UN-6 only) with Weld No. 1.

Step 5. Weld [cap (6-2-2) to tube (6-2-1) UN-4, UN-5] or [cap (6-2-4) to tube (6-2-5) UN-6 only] with Weld No. 2. Leak check to $< 1 \times 10^{-9}$ cc/sec, dye check and x-ray. Finish machine after welding.

The following steps are shown on E-007 (primary containment weldment):

Step 6. Weld cap (35-2) to shell (35-1) with Weld No. 1; machine ID and OD of weld smooth and flush. Dye-check and x-ray.

Step 7. Weld tubes (35-3) and (35-4) to cap (35-5) with Welds No. 2 and 3.

Step 8. Weld test cap (35-5) to shell (35-1) with Weld No. 4. Leak check to $< 1 \times 10^{-9}$ cc/sec. Welds 2, 3, and 4.

Step 9. Pneumatic pressure test primary containment weldment (35) to 1640-1700 psig @ room temperature in accordance with Section III, ASME Boiler and Pressure Vessel Code, Paragraph N-713.

Step 10. After pressure test is complete, (Step 9), cut off to 20 39/64 dimension. Reinspect for dimension tolerance after pressure test. Dye-check and x-ray.

The following steps are shown on E-013:

Step 11. Weld bar (7-1-2) to outer end cap (7-1-1) with Weld #1. Dye check.

Step 12. Assemble Zr sleeve (7-2) with outer end cap weldment (7-1) and make Weld 4. After machining ID of Weld 4, dye-check, x-ray and leak check.

Step 13. Assemble transition joint (7-4) with Step 12 and make Weld 2.

Step 14. Weld tube (7-7) to seal plate (7-6) with Welds 6 and 7. Dye check.

Step 15. Assemble seal plate (7-6) over transition joint (7-4) (Step 13), orient seal plate (7-6) in relation to TE holes (Sec. F-F, Dwg. E-013) and tack-weld seal plate (7-6) to transition joint (7-4) at 19/64 dim. for bench test purposes only.

Step 16. Assemble flange (7-5) over transition joint (7-4) and make Weld #3. Dye check.

Step 17. Thread TE's (7-3) through bulkhead (7-8) and tube (7-7) into proper locations and hold in place by banding (13). For calibration test see dwg. E-10440-R-001. Complete Weld #8. Dye check. Check and record TE resistances.

Step 18. After mockup for calibration test are complete, cut off transition joint (7-4) to 21 63/64 dimension, and remove tack-welds from (7-4) and (7-6).

Step 19. After completing Step 36, complete Step 20.

Step 20. Orient seal plate (7-6) in relation to TE holes (Sec. F-F, Dwg. E-013) at 19/64 dim. and make Weld #5, dye-check and x-ray.

The following steps are shown on E-016:

By M & C

Step 21. (Bottom Fuel Element UN-4 (6-17)) Place bottom cap (6-17-1), liner (6-11-6), flat washer (6-11-10), spherical spacer (6-11-3), flat washer (6-11-2), spherical spacer (2 ea.) (6-11-3), flat washer (6-11-4), spacer (6-11-9), fuel pellets (10 ea.) (6-15-1), spacer (6-11-9), flat washer (6-11-4), spherical spacers (2 ea.) (6-11-3), flat washer (6-11-2), spherical spacer (6-11-3), flat washer (6-11-10), and top cap (6-11-1) into cladding (6-11-7). Complete Welds Nos. 5 and 6. Dye-check and x-ray Weld No. 5 and 6. Set aside for further assembly.

By M & C

Step 22. (Middle Fuel Element UN-4 (6-14)) Place bottom cap (6-11-8), liner (6-11-6), flat washer (6-11-10), spherical spacer (6-11-3), flat washer (6-11-2), spherical spacer (2 ea.) (6-11-3), flat washer (6-11-4), spacer (6-11-9), fuel pellets (10 ea.) (6-11-5), spacer (6-11-9), flat washer (6-11-4), spherical spacers (2 ea.) (6-11-3), flat washer (6-11-2), spherical spacer (6-11-3), flat washer (6-11-10), and top cap (6-11-1) into cladding (6-11-7). Complete Welds Nos. 3 and 4. Dye-check and x-ray Weld No. 3 and 4. Set aside for further assembly.

By M & C — Step 23. (Top Fuel Element UN-4 (6-11)) Place bottom cap (6-11-8), liner (6-11-6), flat washer (6-11-10), spherical spacer (6-11-3), flat washer (6-11-2), spherical spacer (2 ea.) (6-11-3), flat washer (6-11-4), spacer (6-11-4), spacer (6-11-9), fuel pellets (10 ea.) (6-11-5), spacer (6-11-9), flat washer (6-11-4), spherical spacers (2 ea.) (6-11-3), flat washer (6-11-2), spherical spacer (6-11-3), flat washer (6-11-10), and top cap (6-11-1) into cladding (6-11-7). Complete Welds Nos. 1 and 2. Dye-check and x-ray Weld No. 1 and 2. Set aside for further assembly.

The following steps are shown on E-016:

By M & C — Step 21. (Bottom Fuel Element UN-5 (6-18)) Place bottom cap (6-17-1), liner (6-11-6), flat washer (6-11-10), spherical spacer (6-11-3), flat washer (6-11-2), spherical spacer (2 ea.) (6-11-3), flat washer (6-11-4), spacer (6-11-9), fuel pellets (10 ea.) (6-11-5), spacer (6-11-9), flat washer (6-11-4), spherical spacers (2 ea.) (6-11-3), flat washer (6-11-2), spherical spacer (6-11-3), flat washer (6-11-10), and top cap (6-11-1) into cladding (6-11-7). Complete Welds Nos. 5 and 6. Dye-check and x-ray Weld No. 5 and 6. Set aside for further assembly.

By M & C — Step 22. (Middle Fuel Element UN-5 (6-15)) Place bottom cap (6-11-8), liner (6-11-6), flat washer (6-11-10), spherical spacer (6-11-3), flat washer (6-11-2), spherical spacer (2 ea.) (6-11-3), flat washer (6-11-4), spacer (6-11-9), fuel pellets (10 ea.) (6-15-1), spacer (6-11-9), flat washer (6-11-4), spherical spacers (2 ea.) (6-11-3), flat washer (6-11-2), spherical spacer (6-11-3), flat washer (6-11-10), and top cap (6-11-1) into cladding (6-11-7). Complete Welds Nos. 3 and 4. Dye-check and x-ray Weld No. 3 and 4. Set aside for further assembly.

By M & C — Step 23. (Top Fuel Element UN-5 (6-12)) Place bottom cap (6-11-8), liner (6-11-6), flat washer (6-11-10), spherical spacer (6-11-3), flat washer (6-11-2), spherical spacer (2 ea.) (6-11-3), flat washer (6-11-4), spacer (6-11-9), fuel pellets (10 ea.) (6-11-5), spacer (6-11-9), flat washer (6-11-4), spherical spacers (2 ea.) (6-11-3), flat washer (6-11-2), spherical spacer (6-11-3), flat washer (6-11-10), and top cap (6-11-1) into cladding (6-11-7). Complete Welds Nos. 1 and 2. Dye-check and x-ray Weld No. 1 and 2. Set aside for further assembly.

The following steps are shown on E-016:

By M & C — Step 21. (Bottom Fuel Element UN-6 (6-19)) Place bottom cap (6-19-1), liner(6-11-6), flat washer (6-11-10), spherical spacer (6-11-3), flat washer (6-11-2), spherical spacer (2 ea.) (6-11-3), flat washer (6-11-4), spacer (6-11-9), fuel pellets (10 ea.) (6-13-4), spacer (6-11-9), flat washer (6-11-4), spherical spacers (2 ea.) (6-11-3), flat washer (6-11-2), spherical spacer (6-11-3), flat washer (6-11-10), and top cap (6-13-1) into cladding (6-13-2). Complete Welds Nos. 5 and 6. Dye-check and x-ray Weld No. 5 and 6. Set aside for further assembly.

By M & C — Step 22. (Middle Fuel Element UN-6 (6-16)) Place bottom cap (6-11-8), liner(6-11-6) flat washer (6-11-10), spherical spacer (6-11-3), flat washer (6-11-2), spherical spacer (2 ea.) (6-11-3), flat washer (6-11-4), spacer (6-11-9), fuel pellets (10 ea.) (6-13-4), spacer (6-11-9), flat washer (6-11-4), spherical spacers (2 ea.) (6-11-3), flat washer (6-11-2), spherical spacer (6-11-3), flat washer (6-11-10), and top cap (6-11-1) into cladding (6-11-7). Complete Welds Nos. 3 and 4. Dye-check and x-ray Weld No. 3 and 4. Set aside for further assembly.

By M & C — Step 23. (Top Fuel Element UN-6 (6-13)) Place bottom cap (6-13-3), liner (6-11-6), flat washer (6-11-10), spherical spacer (6-11-3), flat washer (6-11-2), spherical spacer (2 ea.) (6-11-3), flat washer (6-11-4), spacer (6-11-9), fuel pellets (10 ea.) (6-13-4), spacer (6-11-9), flat washer (6-11-4), spherical spacers (2 ea.) (6-11-3), flat washer (6-11-2), spherical spacer (6-11-3), flat washer (6-11-10), and top cap (6-13-1) into cladding (6-13-2). Complete Welds Nos. 1 and 2. Dye-check and x-ray Weld No. 1 and 2. Set aside for further assembly.

The following steps are shown on D-006:

Step 24. Assemble NaK blanket gas out tube (34) with fill tube (6-3-3), NaK blanket gas in tube assembly (44) with fill tube (6-3-3), (fill tubing must be superclean on ID and polished in area of braze before assembly). Furnace braze as specified by M & C Division. Helium leak check to $< 1 \times 10^{-9}$ cc/sec.

Step 25. Install Step 24, center rod (6-3-2) and the thermocouples (6-3-4 UN-5 only) and (6-3-6) into bulkheads (6-3-1 UN-4 and UN-5) or (6-3-7 UN-6 only) and (6-3-5) (maintaining dimensions as shown to length). Check and record TE junction dimension. Check TE resistance with precision galvanometer and record. NOTE: orientation of .030 diam hole in pt. 6-3-2.

Furance braze to bulkhead (6-3-1) only, as specified by M & C Division. Helium leak check to $< 1 \times 10^{-9}$ cc/sec. Take and record resistance reading to all thermocouples after brazing.

Step 26. Install outer control gas tube (43) and inner control gas tube (8) into bulkhead (6-3-5). Maintaining 1 25/32 dimension and orientation of Section A-A, Dwg. E-002, furnace braze all TE's and tubes to bulkhead (6-3-5) as per M & C Division. Helium leak check to $< 1 \times 10^{-9}$ cc/sec. Take and record resistance reading to all thermocouples after brazing.

The following steps are shown on E-003:

Step 27. Assemble spiders (6-10), (6-8) and (6-6). Spiders (6-8) and (6-10) may require surface grind for proper clearance.

Step 28. Assemble fuel element subassemblies (Steps 21, 22, and 23) using tungsten wire (6-1) through proper holes in end caps. Wrap tungsten wire 1/2 turn to side opposite reactor as shown in Section A-A and twist to secure.

Step 29. Attach fuel element assemblies to thermocouple assembly (6-3) using tungsten wire (6-1) through hole in center rod. For orientation in relation to TE's and reactor, see Note #1 and Section C-C before assembly of wire (6-1).

Step 30. Attach thermocouples with TE band wires (6-4) using a .005 piece of shim stock between thermocouple and cladding until band wires are twisted to secure, then remove shim stock in presence of project engineer per length dimensions shown. Photograph assembly along with NaK vessel and primary container and clean all parts prior to Weld #1.

Step 31. Slip NaK vessel weldment (6-2) over fuel can assembly UN-4, or UN-5 or UN-6; take information x-ray from pin clearance in bottom cap prior to welding. Make Weld #1. Dye check, x-ray and leak check to $< 1 \times 10^{-9}$ cc/sec.

Step 32. Evacuate NaK system, purge twice with dry-helium. Leave at a vacuum of 10 microns or less for 18 hours.

Step 33. Fill capsule with 26 cc NaK to specified level. X-ray for NaK level and record information. Cut off 1/16 inch tube while back purge thru NaK system; cut off 1/8 inch tube while back purge thru NaK system. Weld 15 NaK fill line closed. Dye-check and x-ray. Silver solder two lines closing control gas and blanket gas exit lines after purging with helium and leaving 10 psig inside and dye-check.

The following steps are shown on E-002:

Step 34. Slip primary containment weldment (35) over capsule assembly (6) radiograph to check .243 gap, and make Weld #16. Dye check, x-ray and leak check to < 1 x 10^{-9} cc/sec.

Step 35. Slip Zr weldment (7) over primary containment weldment (35) and place in welding fixture and check for alignment.

Step 36. Check .125" gap at bottom cap Zr weldment and record. Make Weld #10. Dye check, x-ray and leak check < 1 x 10^{-9} cc/sec.

Step 37. Weld bulkhead (6-3-5) to elbow weldment (16) with Weld #17. Dye check, x-ray and leak check < 1 x 10^{-9} cc/sec.

Step 38. Install Items (12), (31), and (32) and follow procedure of flame check; record reading (standard). The flame check and tightening of parts to be witnessed and record.

Step 39. Assemble tubes (1) and (2) and complete Welds Nos. 18, 6, and 20; dye check and x-ray, protect TE's with shim stock. Check TE resistance after welds (see Step 20).

Step 40. Locate and orient offset "Y" (41) and complete Weld #5. Dye check and x-ray. Install gas tube bulkhead (21) and complete Weld #7; dye check and x-ray.

Step 41. Insert pump-out tube (22) and silver solder (6) tubes to gas bulkhead (21). Clean brazing residue.

Step 42. Attach extension wires (11) and (36) to thermocouples. Flame check joints. Check and record TE resistances. See project engineer for location of TE-X07. Prepare TE and wire in specified location.

Step 43. Install Step 2 and complete Weld #4, dye check and x-ray. Wrap TE with stainless steel shim stock before making Weld #4.

Step 44. Position connector assembly (9) to approximately 2 inches above adapter (10) working through opening. Attach thermocouple extension wire to proper connector pin (see connector schedule). Match wire materials. TE hookup to be checked and recorded.

Step 45. Position connector assembly (9) against adapter (10), slide sleeve on connector assembly into position over adapter (9) and tack Weld Nos. 1 and 2. Vacuum leak check to < 1 x 10^{-9} cc/sec. Complete Welds No. 1 and No. 2. Dye-check only.

Step 46. Pressure check as follows:

46-1 - Apply 1640-1700 psig N_2 to inner control gas line. Wait five minutes.

46-2 - Evacuate through outer control gas lines. Leak check to $< 1 \times 10^{-9}$ cc/sec.

46-3 - Holding N_2 pressure, apply 1800-1875 psig argon pressure through outer control gas lines. Wait five minutes.

46-4 - Apply helium pressure of ~ 50 psig to inner control gas line.

46-5 - Evacuate through outer control gas lines. Leak check to $< 1 \times 10^{-9}$ cc/sec.

46-6 - Evacuate through vent line of gas bulkhead to check T connector in inner control gas and NaK blanket gas lines.

46-7 - Release helium pressure.

46-8 - Leak check to $< 1 \times 10^{-9}$ cc/sec outer can by spraying helium on external welds while outer control gas lines are evacuated.

46-9 - Take information radiograph.

Step 47. Attach leak detector to pump-out tube (22). Spray helium on all external welds above bulkhead (pt. 6-3-5) and silver solder joints of tube bulkhead (21).

Step 48. Install and thread 24 TE's through tubing (4).

Step 49. Epoxy seal area above bulkhead (7-8) as shown on Dwg. E-013. Install hose clamp (7-9).

Step 50. Slide pinch valve subassembly (Step 3) over gas lines and complete Weld No. 8; dye-check and x-ray. Check for proper orientation of pinch valve before welding.

Step 51. Attach Part No. 42 to pinch valve facility tube (24) and tube (3) with shim strap (13) and tack weld securely. (Do not weld to Part 3 or 24.)

Step 52. Paint gas and NaK tubes 2 inches from ends and 2 inches from surface "Y" as per color code.

Step 53. Put neutron absorber (9-5) in part (9).

Step 54. Check TE resistance with Wheatstone bridge and record.

Step 55. Attach support bracket (5) to capsule and photograph capsule in mockup after adjusting. Support bracket at (mockup midplane bracket), and approval by engineer.

Step 56. Evacuate control gas system, twice with dry helium. Silver solder lines shut with 10 psig helium.

Step 57. Make Weld 13, 14, 27, and 28; dye-check and x-ray. In assembly fixture freeze NaK before laying down; keep frozen until placed in vertical position.

Step 58. Install "O" ring on pinch tube adapter.

Step 59. Ship capsules to reactor by freezing capsule end with dry ice and installing in special shipping crate.

APPENDIX E

Table E.1. Postirradiation diameter measurements of the NaK container from capsule UN-4

Location measured (in. from top of container)	Diameter (in.)	
	0°	90°
2	0.6344	0.6348
3	0.6335	0.6321
4	0.6346	0.6325
5	0.6361	0.6332
6	0.6375	0.6334
7	0.6383	0.6342
8	0.6381	0.6342
9	0.6376	0.6346
10	0.6372	0.6335
11	0.6388	0.6328
12	0.6374	0.6348
13	0.6380	0.6359
14	0.6384	0.6371
15	0.6392	0.6384
16	0.6395	0.6383
17	0.6395	0.6386
18	0.6363	0.6396

Table E.2. Postirradiation diameter measurements of the NaK container from capsule UN-5

Location measured (in. from top of container)	Diameter (in.)	
	0°	90°
3	0.6351	0.6359
4	0.6363	0.6368
5	0.6359	0.6379
6	0.6365	0.6393
7	0.6369	0.6398
8	0.6372	0.6388
9	0.6382	0.6396
10	0.6370	0.6382
11	0.6385	0.6385
12	0.6390	0.6387
13	0.6390	0.6390
14	0.6392	0.6392
15	0.6386	0.6389
16	0.6390	0.6365
17	0.6381	0.6371
18	0.6361	0.6403

Table E.3. Postirradiation diameter measurements of the NaK container from capsule UN-6

Location measured (in. from top of container)	Diameter (in.)	
	0°	90°
2	0.6135	0.6139
3	0.6142	0.6134
4	0.6141	0.6136
5	0.6138	0.6146
6	0.6150	0.6145
7	0.6157	0.6138
8	0.6163	0.6154
9	0.6169	0.6162
10	0.6175	0.6168
11	0.6173	0.6167
12	0.6178	0.6172
13	0.6191	0.6165
14	0.6181	0.6169
15	0.6176	0.6172
16	0.6166	0.6173
17	0.6174	0.6169

Table E.4. Postirradiation weight and diameter measurements of the fuel pins from capsule UN-4

Fuel pin No.	Weight (g)	Location measured (in. from top of pin)	Diameter[a] (in.)	
			0°	90°
10 (top)	102.195	0.5	0.3723	0.3724
		1.0	0.3727	0.3726
		1.5	0.3728	0.3725
		2.0	0.3730	0.3728
		2.5	0:3728	0.3729
		3.0	0.3727	0.3732
		3.5	0.3729	0.3731
		4.0	0.3730	0.3730
11 (middle)	100.946	0.5	0.3714	0.3714
		1.0	0.3720	0.3719
		1.5	0.3724	0.3722
		2.0	0.3724	0.3723
		2.5	0.3724	0.3724
		3.0	0.3726	0.3724
		3.5	0.3724	0.3724
		4.0	0.3721	0.3726
12 (bottom)	105.002	0.5	0.3734	0.3738
		1.0	0.3768	0.3769
		1.5	0.3784	0.3777
		2.0	0.3784	0.3794
		2.5	0.3782	0.3785
		3.0	0.3784	0.3777
		3.5	0.3754	0.3750
		4.0	0.3728	0.3727

[a]0° orientation is defined as the side of the fuel pin that faced the reactor during irradiation.

Table E.5. Postirradiation weight and diameter measurements of the fuel pins from capsule UN-5

Fuel pin No.	Weight (g)	Location measured (in. from top of pin)	Diameter[a] (in.)	
			0°	90°
13 (top)	102.594	0.5	0.3725	0.3728
		1.0	0.3728	0.3729
		1.5	0.3734	0.3730
		2.0	0.3736	0.3732
		2.5	0.3737	0.3735
		3.0	0.3738	0.3734
		3.5	0.3742	0.3734
		4.0	0.3737	0.3734
14 (middle)	105.547	0.5	0.3726	0.3733
		1.0	0.3790	0.3800
		1.5	0.3816	0.3838
		2.0	0.3821	0.3844
		2.5	0.3819	0.3814
		3.0	0.3797	0.3784
		3.5	0.3761	0.3756
		4.0	0.3729	0.3729
15 (bottom)	103.310	0.5	0.3722	0.3719
		1.0	0.3725	0.3722
		1.5	0.3732	0.3727
		2.0	0.3729	0.3728
		2.5	0.3734	0.3730
		3.0	0.3735	0.3733
		3.5	0.3733	0.3735
		4.0	0.3731	0.3730

[a]0° orientation is defined as the side of the fuel pin that faced the reactor during irradiation.

Table E.6. Postirradiation weight and diameter measurements of the fuel pins from capsule UN-6

Fuel pin No.	Weight (g)	Location measured (in. from top of pin)	Diameter[a] (in.)	
			0°	90°
16 (top)	69.547	0.5	0.3744	0.3739
		1.0	0.3749	0.3746
		1.5	0.3750	0.3745
		2.0	0.3762	0.3750
		2.5	0.3757	0.3750
		3.0	0.3750	0.3752
		3.5	0.3748	0.3747
		4.0	0.3748	0.3747
17 (middle)	93.444	0.5	0.3724	0.3724
		1.0	0.3728	0.3728
		1.5	0.3727	0.3735
		2.0	0.3728	0.3741
		2.5	0.3729	0.3736
		3.0	0.3729	0.3732
		3.5	0.3729	0.3730
		4.0	0.3730	0.3731
18 (bottom)	70.309	0.5	0.3743	0.3739
		1.0	0.3754	0.3747
		1.5	0.3757	0.3750
		2.0	0.3777	0.3768
		2.5	0.3768	0.3762
		3.0	0.3762	0.3755
		3.5	0.3750	0.3751
		4.0	0.3748	0.3748

[a]0° orientation is defined as the side of the fuel pin that faced the reactor during irradiation.

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